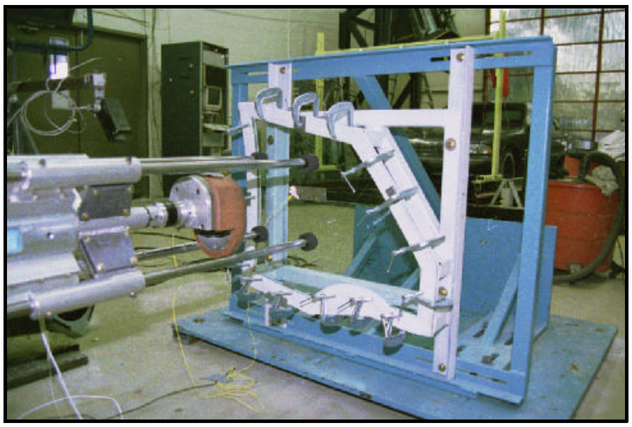
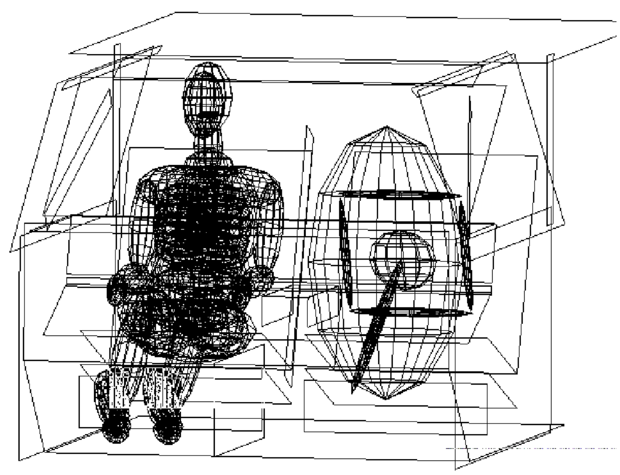
Ejection Mitigation Using Advanced Glazing

A Status Report, November 1995





The Advanced GlazingResearch Team

NHTSA

People Saving People

On the Road for a Healthier Future

TEAM GLAZING

Advanced Glazing Research Team

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1 EXECUTIVE SUMMARY

In response to the National Highway Traffic Safety Administration Authorization Act of 1991, the agency initiated research programs concerning motor vehicle rollover protection. As part of that research, the agency has conducted a crashworthiness research program to evaluate ways to reduce the number of fatalities due to ejection. The program was expanded from side impact ejections to include ejections from rollover, front, and rear impacts.

An average of 7,492 people are killed and 9,211 people are seriously injured each year in passenger cars, light trucks and vans because of partial or complete ejection through glazing. Of these, 4,557 fatalities are associated with vehicle rollovers. Advanced ejection-mitigating glazing at the right and left front side windows could save 1,313 lives saved and 1,290 serious injuries prevented per year.
From an economic standpoint, the total cost per year to society will be between $563,463 and $931,827 per life saved, depending on the material selected by the manufacturers. This estimate is based on an estimated annual incremental cost of $768,000,000 ($48 per vehicle for front, side windows) if trilaminate glass-plastic-glass was used to $1,270,080,000 ($79 per vehicle for front side windows) if rigid plastic was used.

Computer simulations and component testing show that head injuries may increase with the use of some alternative side glazings. For impacts into some such glazings, there appears to be very little increase in HIC value over those produced from impacts into standard tempered glass. For others, there may be an increase of 500 or more (as measured by the free-motion headform in 24 kmph impacts).

We recommend continuing research to further evaluate the safety potential of advanced glazing materials and to measure the performance characteristics of the prototype systems. These studies include expanded computer modeling beyond rollover type accidents, to planar accident simulations, testing repeatability and reproducability, development of injury criteria, full scale vehicle testing, and additional vehicle design testing. We also recommend soliciting additional automotive industry cooperation in the development and testing of modeling techniques, test procedures and vehicle designs.

2 BACKGROUND

2.1. ANPRM On Side Impact Ejection in 1988

The National Highway Traffic Safety Administration (NHTSA) published two Advance Notices of Proposed Rulemaking in 1988 announcing that the agency was considering making a proposal of requirements for passenger vehicles intended to reduce the risk of ejections in crashes where the side protection of the vehicle was a relevant factor. One notice (53 FR 31712, August 19, 1988) dealt with passenger cars. The other notice (53 FR 31716, August 19, 1988) dealt with light trucks. The agency reported that a significant number of fatalities and serious injuries involved the partial or complete ejection of occupants through the doors or side windows.

The agency reported at that time that based on the 1982-1985 Fatal Accident Reporting System (FARS) that 19.5 percent of the fatalities each year were from complete ejection and 4.3 percent were from partial ejection of the occupant through glazing. Data from the National Crash Severity Study (NCSS) showed that for passenger car occupant fatalities involving ejection, 34 percent were ejected through the side windows. Several studies had shown that ejection increases the probability of an occupant's death or serious injury several times over that of non-ejected occupants.

NHTSA believed that new side window designs, incorporating different glazing/frames, may be able to reduce the risk of ejections. The agency pointed out that windshields already contained an inner layer of plastic that mitigated ejection. It was thought that either trilaminate windshield-type glass or side glass with an additional layer of plastic may be suitable materials to mitigate ejection. The agency also suggested a method of anchoring these glazings to the window frame. The plastic portion of the glazing would have to be encapsulated in a frame. The frame could be designed to accommodate movable windows.

At that time, NHTSA suggested that one performance approach would be to use a 40-pound glazing device, requiring that the device not penetrate the plastic layer of a side window at 20 miles per hour, an estimated typical contact speed.

Numerous comments were received on the 1988 ANPRM. Major issues were raised concerning the proposal. First, the safety benefits were not quantified. The injury criteria were not specified for side impact. The practicability of glazing designs were questioned and had never been demonstrated. The cost was considered high. And finally, there was no objective, repeatable test procedure proposed.

Not only was it not clear that ejection mitigating plastic would reduce injuries and fatalities, but questions arose as to whether this material would actually increase injuries.

The head injury criteria (HIC), neck load, and lacerations were discussed by the commenters. The HIC values for side impact had not been shown to correlate to actual injuries. Also, since the agency was proposing to use a heavier test device than is currently used for HIC, there had not been any development of the HIC for these heavier test devices. Ford suggested that neck loads should be measured. Even though this may not prove to be practically difficult, it was an issue that was brought up and will have to be addressed. Finally, one glass manufacturer suggested laceration be measured. The commenters reported that there were significant practicability problems with glazings that would be used in ejection-mitigating designs. The materials that are currently being considered for ejection mitigation did not appear to be sufficiently durable. Also, there had not been any production of an ejection-mitigating encapsulated design by a vehicle manufacturer.

The National Highway Traffic Safety Administration Authorization Act of 1991 mandated that the agency initiate rulemaking on rollover protection. To fulfill this requirement, the agency published an Advanced Notice of Proposed Rulemaking (ANPRM) on January 2, 1992, (57 FR 242) to solicit information concerning rollover crashes, to assist the agency in planning a course of action on several rulemaking alternatives. Forty-two comments were received from vehicle manufacturers, safety groups, retailers of aftermarket automotive equipment, automotive consultants, and a concerned citizen.

Subsequently, a Rulemaking Plan titled "Planning Document for Rollover Prevention and Injury Mitigation Docket 91-68 No. 1" was published for public review on September 29, 1992, (57 FR 198). The planning document outlined crash avoidance and crashworthiness rulemaking approaches to reduce rollover-related injuries and fatalities. This document included a section concerning ejection mitigation using glazing.

Three comments were received on the glazing program: Motor Vehicle Manufacturers Association (MVMA), Chrysler Corporation (Chrysler), and Mitsubishi Motors Corporation.

MVMA stated:

> "MVMA also agrees with NHTSA that additional research is needed before rulemaking is proposed on glass-plastic glazing or door latches. The practicability of glass-plastic glazing needs to be established. Although the laboratory tests have indicated possible benefits of plastic glazing, it has not been shown that existing materials are appropriate for use in all windows or that existing manufacturing technology will support large-scale production. Consumer acceptance also is unknown. Both practicability and feasibility need to be demonstrated before broad rulemaking occurs. MVMA has petitioned NHTSA to amend existing rules to allow promising new plastic glazing materials to be used by manufacturers in fixed or hinged windows rearward of the B-pillar. The experience with the new materials needs to be evaluated before NHTSA proposes further regulatory action."

Chrysler commented:

> "Chrysler has supported the MVMA petition to NHTSA to amend the current rules to add

to the variety of plastic glazing materials that are available to vehicle manufacturers for windows behind the B-pillar. The experience with these applications should be reviewed before additional rulemaking on plastic glazing is undertaken."

"The practicability of the use of glass-plastic glazing materials in movable side windows has not been established. It is one thing to support a piece of glass-plastic glazing in the side window opening of a vehicle to demonstrate in a laboratory test that it can retain an occupant, and quite another to produce in significant volume a movable window assembly with that capability. The glazing must be supported on at least three sides so that, even when partially open, the plastic inner layer can still serve as a "net" to impede occupant ejection. The side supports have to be parallel, which dictates a divider bar and a triangular vent window in front doors. The divider bar reduces visibility through the window opening and affects outside rearview mirror placement and visibility with the mirror...."

"Chrysler supports NHTSA's objective to reduce injury by reducing ejection of occupants in a crash. The available evidence overwhelmingly shows that most ejected occupant are unbelted. The primary countermeasure for ejection should be to increase occupant belt use."

Finally, Mitsubishi commented:

"As we mentioned earlier, an increase in seat belt use has the potential to be extremely beneficial in reducing rollover fatalities. For this reason alone, NHTSA should enact more aggressive efforts to increase the seat belt use rate for passenger cars and light trucks."

"The addition of a frame around the glazing is under investigation by NHTSA as a possible method for preventing ejections. We believe there are numerous problems associated with this method and they still need to be examined, such as whether this will impede the driver's field of vision, whether a glass/plastic glazing within a frame will smoothly and easily elevate and descend in the door throughout the vehicle life, and whether this method will be cost effective. We believe it is premature to make any rulemaking on this until seat belt usage rates are substantially increased: only then can it be determined if such rulemaking would be cost effective."

On July 1, 1994, the agency created a cross-agency research team to expedite the research and analysis of the problem of vehicle ejection out of glazing. This Advance Glazing Research Team has developed analytical and research tools to evaluate the problem of ejection, and to measure potential mitigating designs. The team has initiated a multi-pronged approach on analyzing advance glazing. The following activities have been conducted.

- Developed and built an impactor that can project 18 kg (40 pounds) at 24 kmph (15 MPH).
- Developed full-vehicle computer models and finite element material models (FEA)
- Monitored technological developments.
- Manufactured and tested prototype encapsulated windows, mounted into modified doors.
- Conducted a cost-and-lead-time analysis
- Conducted a benefit analysis

These issues will be discussed in more detail later in the report.

3 SAFETY NEED

3.1 Summary

Partial or complete occupant ejections out of windows were associated with **7,492 fatalities**, **25 percent** of all light vehicle fatalities in 1993. Of these fatally-injured occupants, 3,536 were completely ejected out windows and 3,956 were partially ejected out windows. In rollover accidents, glazing-related partial or complete ejections accounted for 4,557 fatalities, or 51 percent of the rollover fatalities 1993. A total of 18,912 people per year were completely ejected out of glazing. Sixty-seven percent of the non-windshield glazing ejections are out of the front, side windows. The highest number of injuries in ejections is head injuries.

3.2. General Ejection Statistics

The agency conducted a review of the number of injuries and fatalities associated with ejections from light motor vehicles, and more specifically, through motor vehicle windows (glazing). The 1993 Fatal Accident Reporting System (FARS) data and the 1988 through 1993 National Accident Sampling System (NASS) data were used. The FARS database includes a report of each fatal crash in the 50 states and the District of Columbia that occured on a public access road. The NASS database is based on a detailed sampling of accidents by 24 field research teams reviewing about 6,000 light vehicle crashes a year.

First, all ejection-related fatalities were identified, regardless of the route of ejection. The 1993 FARS indicated 29,998 people were killed as occupants of cars, light trucks, passenger vans, or utility vehicles. Twenty-seven percent of these fatalities were reported to have been ejected from their vehicles; **22 percent** were completely ejected and **five percent** were partially ejected. Partial ejection is defined as having some portion of, but not all of, the occupant's body outside of the motor vehicle during the crash. The FARS data are shown in Table 3.1.

Table 3.1: Ejection Status for Occupant Fatalities
in Light Passenger Vehicles in 1993 FARS

Event	Fatalities	Percentage
Not ejected	21,812	73%
Completely ejected	6,580	22%
Partially ejected	1,482	5%
Unknown whether ejected	124	-
Total	29,998	100%

The more-detailed NASS data indicate the annual average fatality estimate derived from the 1988 to 1993 data are about 17 percent lower than that from FARS. In 1993, the FARS system reported 29,998 people killed, while the NASS data system estimate for fatalities for 1993 is 24,838 people. NASS data are most useful in showing percentages of distributions of subcategories of the crash events. Therefore, in the following analyses and discussions, the total number of fatalities identified in the FARS database will be used as the total and the percentages from the NASS database will be used for the sub distributions of this total.

The NASS data used for this analysis , include glazing-related ejection injuries for motor vehicles with Gross Vehicle Weight Ratings (GVWR) of 4536 kilograms (10,000 pounds) or less. Twenty-one percent of occupant fatalities were complete ejections from the vehicles (Table 3.2); this is essentially the same as the percentage indicated by FARS (22 percent). However, the NASS data suggest that FARS is unable to identify about two-thirds of the partial ejections; 16 percent of fatalities were estimated to have been partially ejected based on detailed NASS investigations, compared to only five percent reported in FARS. In total, **37 percent** of the fatalities were related to partial or complete ejections through all vehicle openings, for an annual average of **10,919** people per year.

For NASS reports of non-fatal serious injuries (Accident Injury Severity (AIS) 3 or greater)[1] , the percentages of complete and partial ejections are markedly less; **8 percent** of the seriously injured survivors had been completely ejected and **6 percent** of the seriously-injured were partially ejected. This may be an indication that when someone is ejected from the vehicle in a crash, there is a high likelihood of death. An estimated **two percent** of all occupants of all light vehicles that were in towaway crashes (without regard to injury outcome) were ejected. An estimate of the distribution of ejection-related injuries is listed below.

Table 3.2: Ejection Status for Involved Occupants
All Portals, in Light Passenger Vehicles,
Annual Average for 1988-1993 NASS, Adjusted to 1993 FARS

Fatalities			
	Cases	Estimate	Percentage
Not ejected	1,867	19,079	63%
Completely ejected	583	6,205	21%
Partially ejected	303	4,714	16%
unknown	88	distributed	distributed
Total	2,841	29,998	100%

Seriously Injured			
	Cases	Estimate	Percentage
Not ejected	4,036	68,550	86%
Completely ejected	452	6,684	8%
Partially ejected	167	4,563	6%
unknown	106	distributed	distributed
Total	4,761	79,797	100%

[1] "Abbreviated Injury Scale, 1990 Revision" Association for the Advancement of Automotive Medicine

All Occupants			
	Cases	Estimate	Percentage
Not ejected	65,722	4,191,430	98%
Completely ejected	1,930	37,122	1%
Partially ejected	876	23,878	1%
unknown	1,300	distributed	distributed
Total	69,828	4,252,440	100%

An average of 61,000 partial and complete ejections out of light motor vehicles occured in 1993, based on the average of the 1988 through 1993 NASS fatalities, weighted to the 1993 FARS data.

3.3 Fatalities and Injuries, Related to Glazing Ejections

In total, there was an average of 7,492 fatalities and 7,982 severe injuries attributed to partial or complete ejection out of glazing, based on an average of the 1988 through 1993 NASS with fatalities, weighted to the 1993 FARS data.

Table 3.3 shows a breakdown of the injury severity, by partial or complete ejection.
For the purpose of this analysis, severe injuries will include AIS 3 through AIS 5 injuries, and minor injuries will include AIS 1 through AIS 2 injuries.

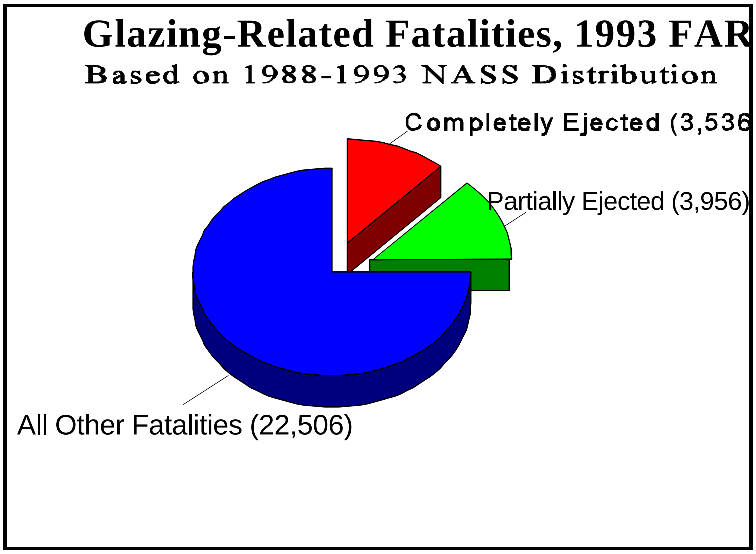
Table 3.3 Injury Severity, by Ejection Type Out of Glazing
Annual Average for 1988-1993 NASS, Adjusted to 1993 FARS

	Fatality	Severe injury
Complete eject	3536	3717
Partial eject	3956	4265

Total	7492	7982

Table 3.3 illustrates that both partial and complete ejections present a safety problem, moreover, partial ejection causes a slightly elevated problem for injuries.

Figure 3.1



In Figure 3.1, note that partial or complete ejections out of light vehicle windows were associated with 25 percent of all light vehicle fatalities. Additionally, these ejection paths are associated with 10 percent of all serious injuries in 1993. Looking at the fatality rate of occupants that were involved in non-ejection-related events and comparing the fatality frequency to the fatality frequency of ejection-related accidents, it is seen that the fatality rate for ejected occupants is 37 times higher, than for non-ejected occupants. A detailed discussion and analysis of the survivability of non-ejected occupants will be presented in the benefit analysis in Chapter 9 of this report.

3.4 Glazing Ejection Routes

For the 37,122 complete ejections annually, 18,922 people (**51 percent**) were ejected out of windows (see Table 3.4). The most common window ejection routes are the right and left front side windows, comprising **37 percent** of all ejections. The left and right side front windows constitute **67 percent** of the non-windshield glazing ejections. The HPR windshields, that were designed to mitigate ejection still account for 8 percent of the complete ejections. Glazing is the portal for **91 percent of partial ejections**. This includes 24 percent who were partially ejected out the windshield and 59 percent who were partially ejected out a front side window.

Table 3.4: Ejection Route for Occupants Ejected from Light Passenger Vehicles, Annual Average for 1988-1993 (NASS)

	Complete Ejection			Partial Ejection		
	Cases	Estimate	Percent	Cases	Estimate	Percent
Windshield	143	3,097	8	204	5,728	24
Front Windows	475	10, 627	29	446	14,155	59
Back Windows	82	1,487	4	38	635	3
Backlight	117	2,903	8	32	1,021	4
Roof Window	31	743	2	8	314	1
Other Glazing	5	55	0	0	0	0
Not Glazing	808	18,211	49	108	2,023	9
Unknown Route	269	(distributed)		40	(distributed)	
Subtotal-Glazing	853	18,912	51	728	21,853	91
Totals	1930	37,122	100	876	23,876	100

The majority of the 10,919 partial and complete ejection fatalities per year are through glazing. On the average **7,492 people** per year are killed involving various forms of glazing ejections; 3,536 people per year are completely ejected out of glazing and die and 3,956 people annually are partially ejected out of glazing and die. Of these, 2,278 of the complete ejection fatalities and 3,146 of the partial ejection fatalities, totaling **5,424 lives**, were attributable to the left and right front side windows.

In Table 3.4, two percent of the partial and complete ejections were attributable to roof openings. But in 1993, 12 percent of all automobiles had a roof opening (not including convertibles). If every automobile had a T-top or a sunroof, the number of ejections would increase dramatically. For example, there are 743 + 314 = 1,057 partial and complete ejections. If this were expanded to every light motor vehicle, there theoretically would could theoretically be over 9,000 roof ejections per year. This points out that roof openings are highly susceptible to ejections because of the direct ejection path for the driver and right front passenger.

3.5 Rollover Versus Non-Rollover Crashes

As indicated previously, this research supports the agency's efforts concerning mitigating rollover accidents, injuries and fatalities. From the 1988 through 1993 NASS data with fatalities, weighted up to the 1993 FARS data, of the 4,252,440 occupants per year involved in tow-away accidents, 378,994 occupants were involved in rollover accidents. Of these, there are 8,929 rollover-related fatalities, from all sources.

Of these rollover fatalities, 4,557 are due to complete or partial ejection out of glazing (See Table 3.5). The remaining 21,069 fatalities in 1993 were attributed to planar (side, front or rear) crashes.

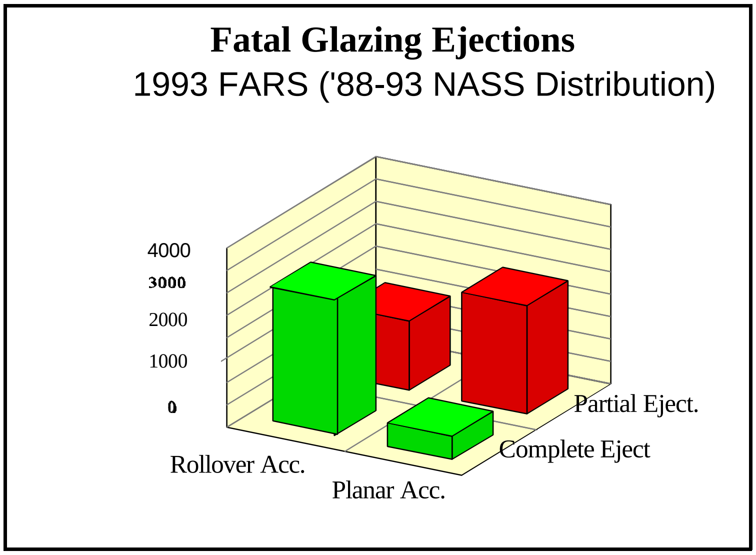
Table 3.5: Fatal Glazing Ejections

Annual Average for 1988-1993 NASS, Adjusted to 1993 FARS

	Rollover	Planar	Total
Complete Ejection	3,016	520	3,536
Partial Ejection	1,541	2,415	3,956
Total	4,557	2,935	7,492

As noted in Table 3.5, ejections are not unique to rollover. There are 2,935 complete and partial ejection fatalities in planar (non-rollover) crashes. Thus, **7,492** people a year are killed in accidents involving partial or complete ejections out of glazing. Sixty-one percent of the glazing ejection fatalities are related to vehicle rollover and 39 percent are due to non-rollover, planar crashes. As noted in Figure 3-2 and Table 3.4, approximately the same number of people are killed in **rollover complete ejections** out glazing and as those killed in **non-rollover partial ejections** out glazing.

Figure 3.2



3.6 Vehicle Type

An analysis was conducted concerning the magnitude of ejections, by vehicle type. There were an average of 61,000 partial and complete ejections per year, as of 1993. Over 40,000 partial and complete ejections per year were out of glazing. Table 3.5 identifies the quantity of ejections by vehicle type.

Table 3.5 Glazing Ejections by Vehicle Type.

Annual Average for 1988-1993 NASS, Adjusted to 1993 FARS

	partial eject	complete eject	total eject	all crashes	Eject percent
passenger car	15,643	11,593	27,236	3,371,127	.8%

utility vehicle	1,128	1,905	3,033	154,014	1.9%
vans	730	1,108	1,830	183,732	1.0%
pickups	4,333	4,265	8,598	528,331	1.6%
other	19	61	80	15,237	.5%
total	21,853	18,932	40,785	4,252,440	1.0 %

3.7 Injuries by Body Regions

Rulemaking also looked at the body regions involved in serious injuries (AIS 3 and greater). For complete and partial ejections, the greatest number of injuries from all vehicle contact sources is to the head.

For complete ejections, head injuries account for **65 percent** of the injuries. The next most common injury site is the arms , accounting for 18 percent, then torso, legs, and finally the neck. Neck injuries are only 3 percent of the injuries.

The windshield with its penetration resistant qualities, accounts for about half of the head injuries, even though only 8 percent of the complete ejections are through the windshield. Also, the windshield is implicated slightly more often in neck injuries, four percent versus three percent among all ejected occupants. It is not clear whether this is a manifestation of the penetration resistance of the glazing or the kinematics of an ejection out of the windshield. Tempered glass windows which shattered during the initial stages of the accident do not cause a significant number of head injuries.

For partial ejections, head injuries constitute **73 percent** of the injuries (even for the tempered windows.) Neck injuries account for an additional 6 percent of these injuries.

3.8 Belt Use Versus Ejection

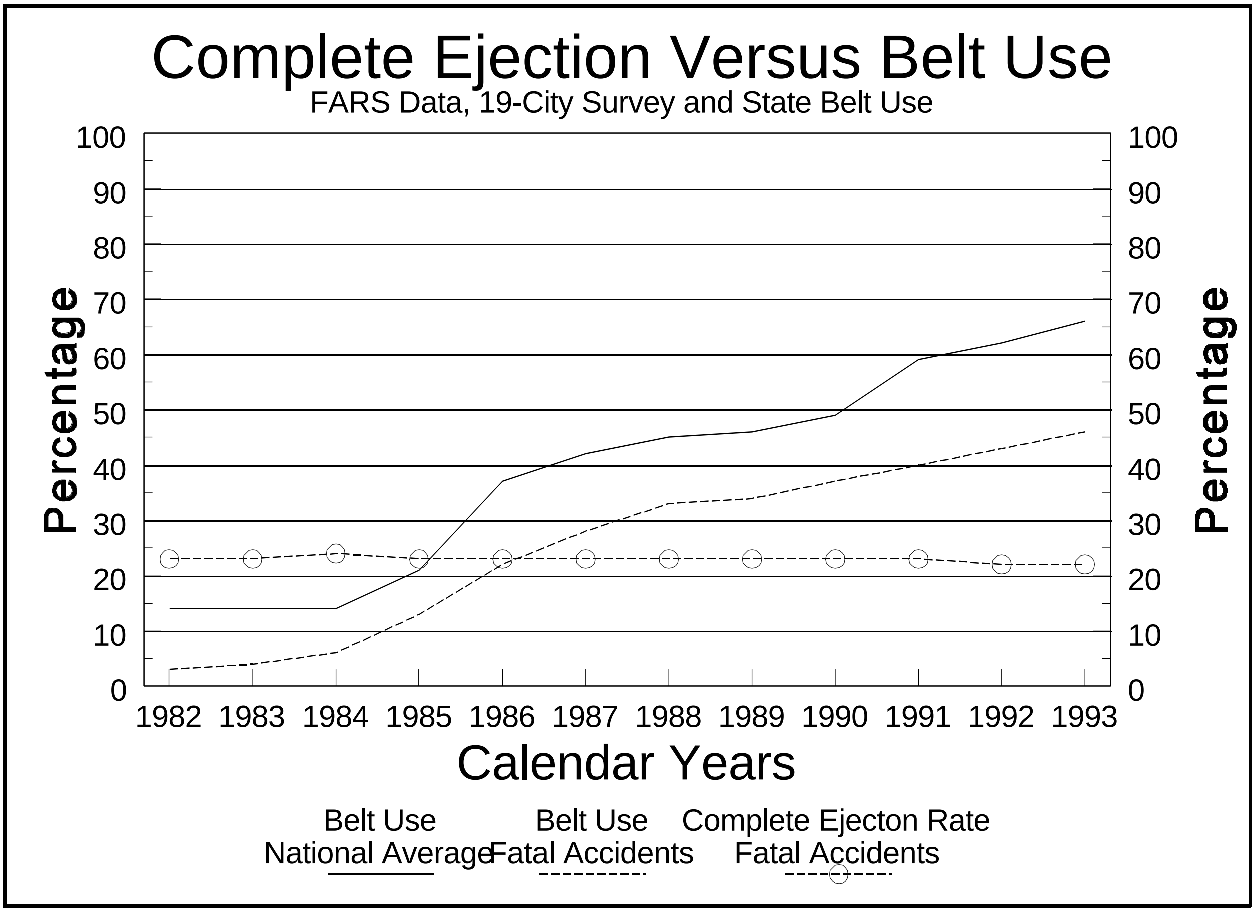
Previously, the agency has shown that virtually all people being ejected are unbelted. In one analysis[2] the agency determined the belt use of ejected drivers, using the 1989 FARS data. That study indicated 98 percent of the completely-ejected drivers and right front passengers were unbelted.

In order to determine the affect of increase safety belt use on the reduction of occupant ejections, an analysis was performed, comparing the two sets of data. As shown in Figure 3.3, to date, increased safety belt use has not caused a concurrent decrease in ejected, fatally-injured occupants .[3]

Figure 3.3

[2]"Occupant Ejections from Light Passenger Vehicles", Table 7, Susan C. Partyka, NHTSA, Docket 88-06-No.3-044

[3]National safety belt use derived from the "19-City Surveys" and current state-reported data. Belt use in fatal accidents, and ejection in fatal accidents derived from the Fatal Accident Reporting System.


Complete Ejection Versus Belt Use
FARS Data, 19-City Survey and State Belt Use
Percentage
100
90
80
70
60
50
40
30
20
10
0
1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993
Calendar Years
Belt Use National Average
Belt Use Fatal Accidents
Complete Ejecton Rate Fatal Accidents

4. ADVANCED SIDE GLAZING SYSTEM

This section describes an integrated system for automotive sidelites used in the Advanced Side Glazing Team's research for occupant ejection mitigation. The research objectives bring together the technologies of glass makers, polymer resin suppliers and automotive modular window suppliers in a joint effort to develop a cost effective occupant retention glazing system with the capabilities to meet the performance criteria. The success of the side glazing modular system to contain the targeted energy levels is highly dependant upon how well the applied energy is transferred from the glazing material to the door frame without encountering failure of the glazing material, failure of the adhesive bond between the glazing material and the framing module, or failure at the framing module/window channel interface. Currently, tempered glass is used in automotive side windows, which offers virtually no resistance to occupant ejection.

4.1 Side Glazing Candidates

The advanced glazings used in this research incorporate three material constructions. The first construction involves a glass-plastic formulation (hereafter referred to as bilaminate) in which a thin plastic film is bonded to the glass. In these formulations, the plastic film actually consist of two or more polymers bonded together resulting in desired performance properties. The second construction is similar to conventional windshields in which a plastic film is laminated in between two glass layers (hereafter referred to as trilaminate). The third construction is a monolithic rigid plastic that has been covered with an abrasion resistant coating and thermoformed to match the curvature of the tempered glass part. The various glazing designs provide the Advanced Glazing Team a wide range of material properties and characteristics to study for a better understanding of containment capabilities.

Previous research has been conducted on two of the advanced glazing formulations. In the early 1980's the NHTSA began research on bilaminate glazing to evaluate its potential for reducing occupant ejections as well as lacerations. Clark and Sursi's original work involved different glass-plastic formulations supplied by Saint Gobain Vitrage and E.I DuPont de Nemours and Company[1].

These early candidates were based on plastic formulations designed for anti-lacerative windshields but applied to tempered side glass. To date, considerable research has been conducted by these and other companies resulting in new side glazing concepts. The following is a brief overview of the alternative side glazing concepts used in this study.

4.1.1 Dupont's Bilaminate Glazing

The E. I. Dupont Company's bilaminate formulation is shown in Figure 4.1. This product has been commercialized since its evaluation in NHTSA's earlier ejection mitigation research and is known as *Sentry-Glas*. It consists of a layer of polyvinyl butyryl (PVB) bonded to a 4.0 mm thick piece of tempered glass. PVB is used exclusively in windshields because of its energy absorption characteristics. Research has shown that the thickness of PVB will affect Head Injury Criterion (HIC) values. Bonded to the PVB is a layer of polyethylene terephthalate (PET), a

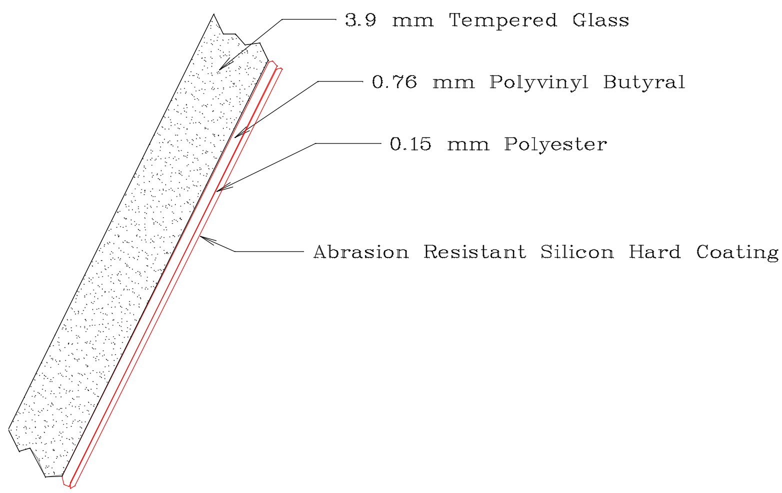


Figure 4.1 Dupont's Bilaminate Glazing Candidate

[1] Clark, C. C., Sursi, P.L., "The Ejection Reduction Possibilities of Glass-Plastic Glazing", SAE Paper 840390, February 1984

polyester known as MYLAR which provides some level of abrasion resistance. For additional wear resistance, a proprietary hard coating has been added.

4.1.2 Saint-Gobain Vitrage's Bilaminate Glazing

Saint-Gobain began applying soft plastic to glass in 1976 when they introduced the idea of an anti-lacerative windshield. Today, Saint-Gobain offers bilaminate side windows to European automotive manufacturers as an anti-theft device. They have also performed significant research in passenger containment areas. Their concept, shown in Figure 4.2, shows a 1.0 mm film made from two formulations of polyurethane. The inner polyurethane layer is formulated to have high energy absorption characteristics. The outer layer provides scratch and abrasion resistance. A characteristic of the polyurethane is that it tends to recover when deformed. Once the surface is punctured, however, permanent deformation will occur.

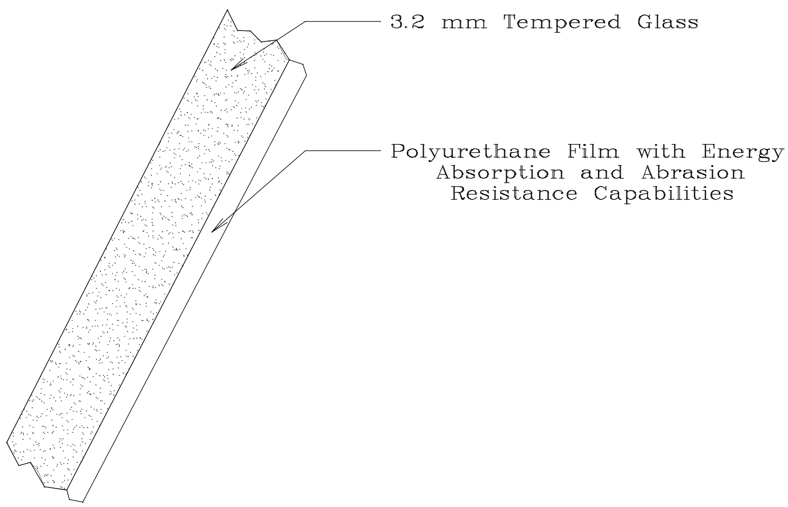


Figure 4.2 Saint Gobain's Bilaminate Glazing Candidate

4.1.3 Monsanto's Trilaminate Candidate

The Monsanto Chemical Company has supplied a trilaminate glazing concept shown in Figure 4.3. The laminate consisting of two 1.85 mm annealed glass plys sandwiching a 0.76 mm film of PVB. The PVB in Monsanto's advanced glazing is commercially known as "Saflex" and is found in many of today's windshields. According to Federal Motor Vehicle Safety Standard (FMVSS) No. 205, this configuration is defined under Item 2, laminated glass, which is currently allowed in side windows. When shattered, annealed glass yields larger and sharper fragments than tempered glass. Monsanto has reported that they are working on a version of this configuration in which the external glass layer is tempered.

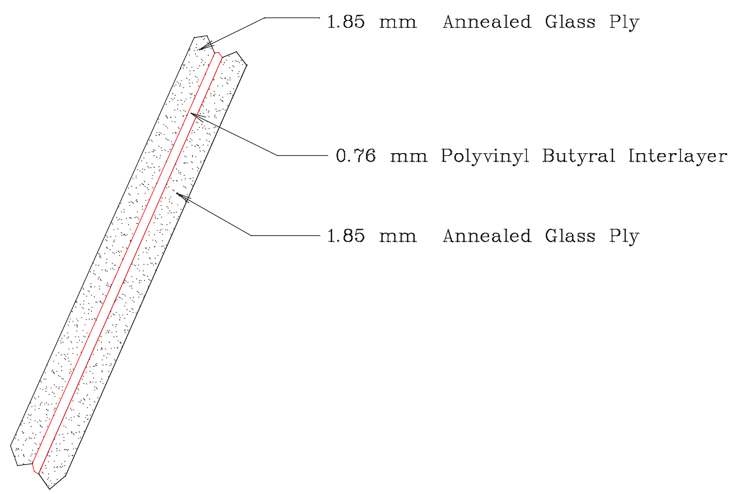


Figure 4.3 Monsanto's Trilaminate Candidate

4.1.4 AGP's Trilaminate Candidate

Advanced Glass Products have a product known as "Noviflex 1-2-1" that has been installed in side windows as a retardant to theft. The manufacturer has stated that some domestic automotive manufacturers have evaluated Noviflex in side windows with regards to injury criteria. The glass on each side of the Noviflex plastic (a nylon) is chemically tempered, which is not as strong as fully (heat) tempered glass. The candidate is shown in Figure 4.4.

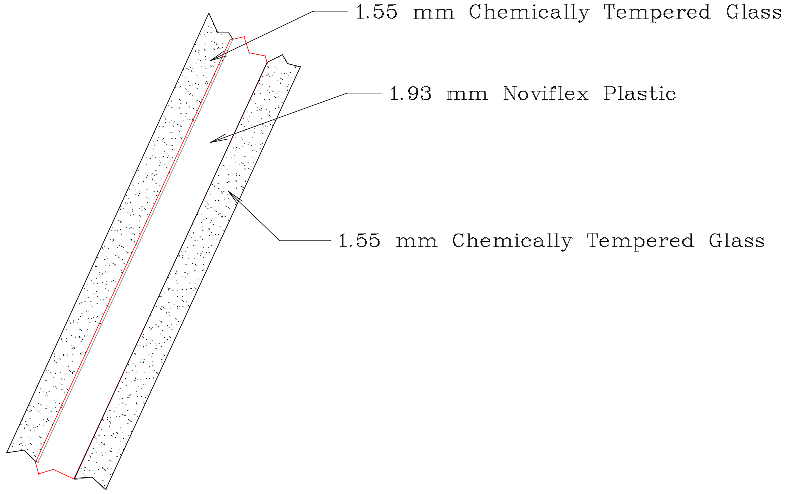


Figure 4.4 AGP's Trilaminate Candidate

4.1.5 Rigid Plastic Glazing Candidate

The rigid plastic alternative is shown in Figure 4.5. The Bayer Corporation has supplied 3.0 mm thick panels of their Makrolon polycarbonate thermoformed to the profile of the Ford LTD. The GE Plastics Division has supplied 4.6 mm flat panels of their Lexan polycarbonate. These panels have been cut and shaped to match the tempered sidelight of choice. The surfaces are coated with

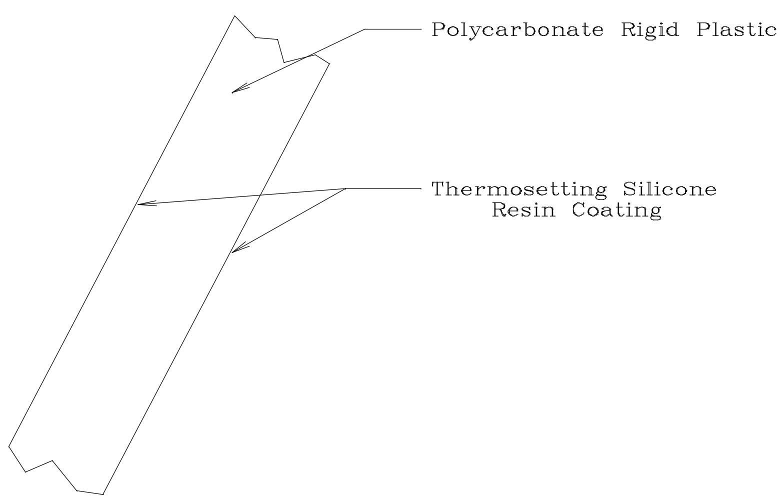


Figure 4.5 Rigid Plastic Candidate

a transparent primer and thermosetting silicone resin (polysiloxene) known as Silvue 211 from

SDC Coatings Inc. The coating provides increased resistance to abrasion, scratches and chemical deterioration. Rigid plastics are currently restricted to areas not requisite for driving visibility.

The material thicknesses shown depict the configurations as they were tested in the research. The thickness of each material will influence its performance in a component level test. Therefore, the thickness of the respective layers of material shown here may change as performance criteria are further defined.

4.2 Window Encapsulation

The manufacture of automotive modular windows has increased dramatically the last ten years. Modular windows increase assembly productivity through ready-to-install automotive glazings and permits the glazings to be mounted flush to the vehicle. A growing portion of rear quarter windows, windshields and back lites are supplied as modules which can be directly attached to the body sheet metal of an automobile. Modular windows are made by encapsulating the window's perimeter with a plastic frame usually made of polyurethane or polyvinyl chloride (PVC).

In Clark and Sursi's earlier work, it was reasoned that the greatest penetration resistance would result if the load was transferred to the window frame. The edges of the glass-plastic windows were encapsulated with a polyurethane mold. The "T" shaped mold restrained the glazing edges within the window frame resulting in increased penetration resistance. This new system also permitted the window to be raised and lowered in a conventional manner. Full window encapsulation with solid steel rod and tube reinforcements was required to contain the target energies. The success of these efforts proved challenging and difficult in transferring the applied load from the plastic film to the frame without encountering either rupture of the film membrane or delamination of the T-edge material. As a result, the difficulty of achieving an adequate adhesion between the glazing material and edge profile limited the energy containment performance.

Excel Industries, a modular window supplier, was contracted to fabricate tooling and provide the cold pour urethane parts that were manually bonded to the glazing material with a urethane adhesive. These parts did not represent the manufacturing process which would be used to produce parts in production volumes. As a result, Excel initiated a program to design and build a production level mold to manufacture encapsulated Ford LTD windows using the T-edge design concept from earlier NHTSA work. The result is a reaction injection molded (RIM) polyurethane system. The mold provides the flexibility to encapsulate from one to four sides of the LTD window, and through the use of removable inserts, other edge profiles can be designed into the mold. As part of their program, Excel has demonstrated that a sufficient bond strength can be obtained between the polyurethane edge and the various glazing materials under investigation to meet the requirements of this early ejection reduction research.

Excel Industries has been contracted to encapsulate the various advanced glazings. Because their original T-edge design extended beyond the glass edges, it would prevent the modular glass from easily being reinstalled inside an existing LTD door without major modifications to the door

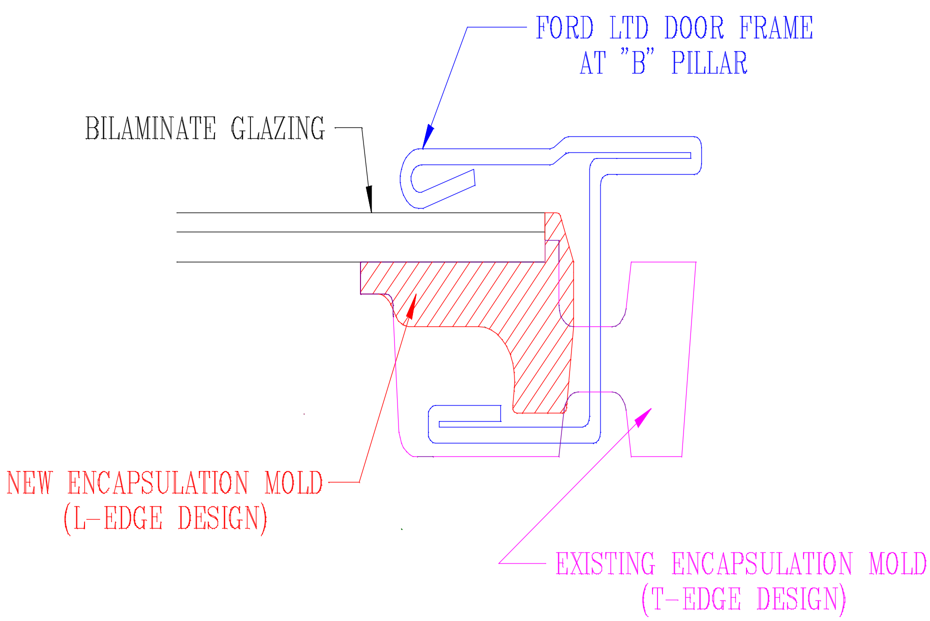


Figure 4.6 Modified Encapsulation Edge vs. Existing T-edge Design

frame. A new edge was conceived that would not add to the width of the glass, allowing the modular glazing to be set inside the existing window frame. In addition, this new “L-Edge” does not impede the ability to raise and lower the glazing. Figure 4.6 illustrates the difference between the edge designs.

After discussions with modular glazing suppliers, it was concluded that it would be highly desirable to have a modular glazing structure with containment capabilities in which the top horizontal edge did not require framing. This configuration would seem to be more acceptable to automobile manufacturers for future designs of flush mounted side glass systems. The advanced glazings in the Ford LTD configuration were therefore encapsulated only along the two vertical edges as shown in Figure 4.7. Although the LTD sidelite is no longer in production, the shape represented by the two vertical edges represents a large majority of sidelite designs in today’s vehicles. With 45 percent of the glazings perimeter being constrained (this includes the

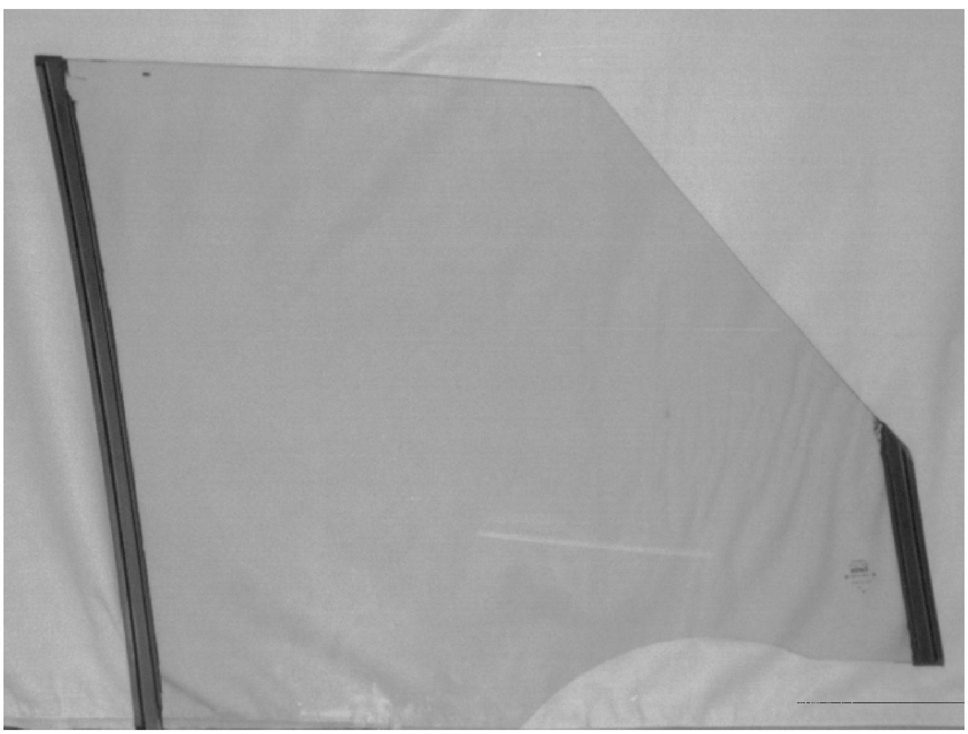


Figure 4.7 Two-Sided Encapsulation Ford LTD Sidelite

bottom edge of the glazing which is attached to the window regulator), the performance of the glazing module was assessed as a worst case. In addition, no reinforcing rods were used to add stiffness to the polyurethane frame.

4.3 Modified Ford LTD Side Door

Modifications to the window frame were required to accommodate the modular glazings and to transfer the load to the vehicle door. The Ford LTD window frame is a roll formed frame section in which the sidelite is contained in U-shaped channels as shown in Figure 4.8. This rather simplistic design along with the L-edge section design affords a simple modification in which 20 gage sheet metal is bent around the interior side of the U-channel and welded in place. The frame was modified only along the vertical edges of the frame above the belt line. The window frame modification is shown in Figure 4.9. Although it was necessary to remove the weatherstripping, this modification did not restrict the window's ability to be raised and lowered.

Figure 4.8   Ford LTD Window Frame (Roll Formed Frame Design

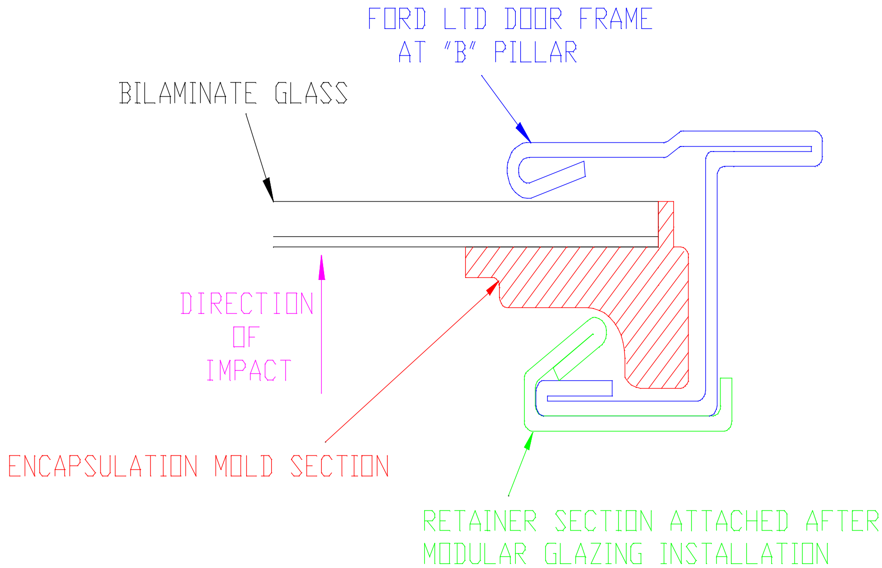


Figure 4.9 Ford LTD Window Frame Modification

5. BIOMECHANICAL ISSUES

When considering the use of ejection mitigating glazings in the side windows of passenger vehicles, there are a few biomechanical issues that should be addressed. These include issues concerning the measurement of head, neck, and laceration injury potential from contact with such glazings. Current side glazings are tempered glass, and while they offer little protection against occupant ejection, they also produce little risk of causing a serious head or neck injury to an occupant from impact with the glass. Due to the fracture characteristics of tempered glass, there is also little risk of serious laceration.

5.1 Head Injury

There are several concepts for ejection mitigating side glazings currently being explored. As a consequence of this safety feature, some of these glazings may be stiffer or may produce head loading over a longer period of time than traditional tempered glass windows, thereby increasing the risk of serious head injury. For this reason, the Advanced Glazing Research Team is exploring methods for measuring the head injury causing potential of these glazings.

The free-motion headform (FMH) established for use in the recent upgrade of FMVSS 201 is currently being evaluated for use in this program[1] (see Chapter 7). The FMH is a Hybrid III head, modified for use as a free-motion impactor. It is unattached from the neck and body of the dummy and has a weight of 4.5 kg (10 lb). Tri-axial accelerations of the headform center of gravity are measured, from which a HIC value can be calculated (hereafter referred to as FMH HIC).

The HIC-1000 criterion was established for use with a full dummy to evaluate the threat of serious head injury from an impact to the front of the head. For this reason, the HIC-1000

[1] FMVSS 201 Final Rule; Volume 60, Number 160; Docket Number 92-28, Notice 4; August 18, 1995.

criterion should not be directly applied to the FMH HIC. First, head impacts to side glazings generally occur to the side of the head. It is well accepted that the side of the human head has a lower injury threshold than the front of the head. That is, a blow to the side of a head will generally produce a more severe head injury than would that same blow to the front of the head. Unfortunately, there is no established side head injury criterion available for use in this program. Therefore, head injury causing potential will likely be evaluated in terms of frontal impacts. The agency has previously concluded that the incorporation of ejection mitigating windshields would not increase the occuance of blunt impact trauma to the head[2]. Another possibility is to limit FMH HIC based on the performance of existing side windows and front windshields.

Second, since the FMH is not attached to the neck and body of the dummy, a blow to the FMH may produce a different resultant acceleration (and thus, HIC value) than would that same blow to the head of a full Hybrid III dummy. To account for this difference, the FMH HIC must be transformed to an equivalent full dummy HIC (hereafter referred to HIC(d)). This same approach was used in evaluating the FMH HIC for the upgrade to FMVSS 201[3]. That transform, established for upper interior impacts, is not necessarily valid for use in glazing impacts.

The reason for this is that the head of a full dummy is attached, but not rigidly, to the neck and body of the dummy. For a very short duration impact, the head acts as a free body, not being influenced by the neck and body. In this case, there should be little difference in the acceleration responses of the FMH and the full dummy head. As the impact duration increases, the influence of the neck and body increases, thus potentially creating a larger difference between the acceleration responses of the two surrogates. Upper interior impacts are typically of a 5 to 15 milliseconds duration, depending on the stiffness of the impact surface. Glazing impacts have

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[2] Kahane, C, "An Evaluation of Windshield Glazing and Installation Methods for Passenger Cars" NHTSA report no. DOT HS 806-693, February, 1985

[3] Willke, Donald T.; "Upper Interior Head Protection, Volume II: Fleetwide Characterization and Countermeasure Evaluation"; Report Number DOT-HS-807-866; November 1991.

notably longer durations, typically 80 to 100 milliseconds, depending on the type of glazing. Therefore, it cannot be assumed that the transform used for upper interior impacts is valid for glazing impacts.

At this time, a FMH-to-full dummy HIC transform has yet to be established for use in the glazing program. Therefore, the HIC values listed in later sections of this report are FMH HIC values and should not be evaluated using the HIC-1000 criterion.

5.2 Neck Injury

Since ejection mitigating glazings will generally allow for greater contact time between the head and glazing than conventional side windows, there is a potential for an increased risk of serious neck injury from such contact. This possibility is being examined in this research program. The approach is to compare the neck loads and moments of a full dummy from impacts into ejection mitigating glazings to those into baseline windows (ie. closed tempered glass and fully open windows), using both testing and computer modeling. In addition to directly comparing the loads and moments measured during the tests, the relative severity of these measurements will be estimated using the injury assessment reference values defined by Mertz[4,5].

The current approach in this research program is to evaluate the ejection mitigating potential of glazings using an 18 kg guided impactor (see Chapter 7) and to evaluate the head injury causing potential of glazings using the FMH. Neither of these procedures allows for the measurement of neck loads. If research shows that there is no increased risk of serious neck injury from the use of ejection mitigating glazings, then the measurement of neck loads during

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4 Mertz, H.J.; “Injury Assessment Values Used to Evaluate Hybrid III Response Measurements;” Attachment I, Enclosure 2 of GM submittal concerning the use of the Hybrid III in FMVSS 208; February 1984.

5 Mertz, H.J. and Patrick, L.M.; “Strength and Response of the Human Neck;” Fifteenth Stapp Car Crash Conference; SAE paper number 710855; 1971.

glazing impacts will not be necessary. If there are indications of an increased risk, then other procedures may be considered.

5.3 Laceration

There are concerns that the use of some types of ejection mitigating glazings may increase the risk of lacerative injuries. Since such injuries are relatively minor (AIS 1 or 2), this issue has not been given as high a priority as the investigations into head and neck injuries. Though minor in nature, facial lacerations can be disfiguring, so there are plans to explore lacerative injuries further. Although NHTSA has not currently accepted the available methods for measuring and evaluating the severity of lacerations, one or two promising methods will be explored in this program.

6. SIMULATIONS OF ROLLOVER ACCIDENTS

6.1 Objective

The objective of this project was to use computer simulations to estimate the injury potential and retention capability of alternative glazing materials in crash events. The computer simulations can provide a viable means for predicting occupant motion during rollover crashes. It allows extensive parametric studies with perfect repeatability. The computer simulations were set up to study the kinematic and dynamic motions of the vehicle and its occupant in selected rollover crashes. The simulations presented in this report are not exact reconstructions of a specific rollover accident, but are intended to be representative of real world accidents, generally.

6.2 Introduction

In this study three rollover crashes were modeled in which an occupant was ejected or made severe contact with the side glazing. These accidents were National Accident Sampling Systems (NASS) investigated cases. Two of these accidents were single vehicle rollover crashes. A vehicle handling simulation software, VDANL [1], was used to reconstruct the vehicle motion up to the point where the vehicle started to roll. The linear and angular velocity at the end of the vehicle handling simulation was then used to drive a MADYMO lumped parameter model of the vehicle to compute its complete rollover motion [2]. A simple one segment MADYMO model of the vehicle simulated the interaction of the vehicle with the ground during the rollover [Figure 6.1]. Finally, the motion of the vehicle obtained from the MADYMO vehicle model was used to drive a MADYMO occupant simulation to calculate the injury parameters [Figure 6.2]. The occupant simulation calculates the interaction between the occupant and the vehicle's interior, including the glazing, and predicts the resulting injury parameters.

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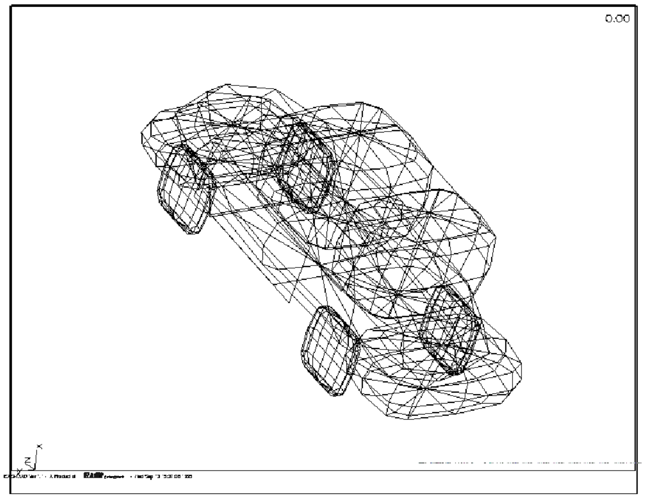
[1] VDANL software user's manual V2.34, STI, 1992

[2] MADYMO User's Manual V5.1, TNO, 1994



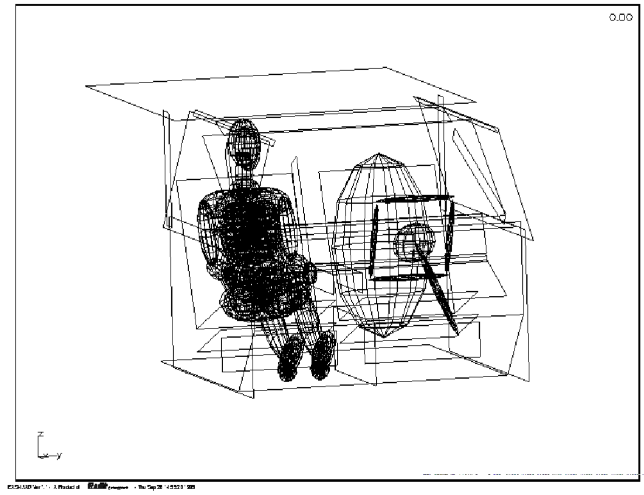


Figure 6.1. MADYMO vehicle model

Figure 6.2. MADYMO occupant model

A matrix of occupant simulation runs was established to study each rollover crash. The parametric simulations were carried out by substituting the contact characteristic (force deflection function) of each type of glazing for the side window. Additionally, a simulation with no glazing was run to model the tempered glass that was broken due to the ground impact. Roof crush was ignored in all the simulations. Hence, the injury caused by the roof deformations were not accounted for in this study. The MADYMO simulations conducted in this study are discussed in the following sections and the matrix of parametric runs is shown in Table 6.1.

Table 6.1 Matrix of parametric simulation runs

	Belted	Unbelted
No glazing	x	x
Tempered glass	x	x
Rigid plastic	x	x
Laminated Safety Glass	x	x
Dupont's glass-plastic	x	x

6.1.1 Material Models

In MADYMO the contact forces between the segment (occupant's body) and planes (vehicle interior) are assumed to be functions of penetration value. For each plane segment contact a Force .vs. Deflection function is defined. The Force-Deflection Functions (FDF) for the following glazing materials were used in the computer modeling.

1. Tempered Glass: The tempered glass is typically used for side window glazing. The properties were taken from reference 3[3].

2. Polymethyl methacrylimide(PMMI): PMMI is a rigid plastic glazing material. These properties were taken from reference 3.

3. Laminated Safety Glass: Impact tests were conducted on several Jeep windshields with 5.9 kg, 9 kg and 18 kg impactor at 16 kmph and 32 kmph. The FDF used for this study are typical for a 5.9 kg impactor test at 16 kmph.

4. Glass-Plastic: The glass-plastic glazing simulated in this study was DuPont's bilaminate glazing. The glazing consists of a layer of polyvinyl butyral (PVB) bonded to tempered glass. A layer of polyethylene terephthalate (PET), is bonded to PVB to provide some level of abrasion resistance. The FDF for the glass-plastic glazing material was obtained from an 18 kg guided impactor test at 24 kmph. The glazing was rigidly fixed at all the edges in the test. Additional simulations are planned that will use properties measured from recently conducted tests on the door mounted glazings (see section 7.0)

6.1.2 Injury Criteria

To estimate the severity of neck injuries, values obtained from the simulations were compared

[3] Reilly, J.K., Miller, P.M., "Headform impact testing of plastic glazing materials", SAE technical paper # 930741

with the injury assessment reference values defined by Mertz [4,5]. The severity of the head injury was estimated by computing the HIC values. The severity of the neck injury was estimated by comparing the neck axial compression and axial tension loads in the simulation with the reference values. The severity of these loads also depend upon the duration of contact. The severity of the neck injury was also estimated by comparing the neck flexion (forward rotation about y axis) and extension (backward rotation about y axis) bending moments in the simulation with the Mertz's reference values. The reference values are shown in Table 6.2. An injury value greater than the Mertz's reference value shown in the table may indicate a potential for significant neck injury.

Table 6.2. Injury Assessment Reference Values for Hybrid III type adult dummies.

Head/Neck Interface	**Mid-Size male**	**Small female**
Axial Compression (N)	4000 for 0 msec 1100 for 30 msec	2668 for 0 msec 734 for 27 msec
Axial Tensile (N)	3300 for 0 msec 2900 for 35 msec 1100 for 45 msec	2201 for 0 msec 1934 for 31 msec 734 for 40 msec
Flexion Bending Moment (Nm)	190	104
Extension Bending Moment (Nm)	57	31

6.2. Rollover of a Toyota Pickup

A NASS reported accident of a Toyota pickup rollover was previously simulated by Wright Patterson AFB [6]. The accident involved a pickup truck and a passenger car. They were both

[4] Mertz, H.J.;" Injury Assessment Reference Values Used to Evaluate Hybrid III Response Measurements", Attachment I, Enclosure 2 of GM submittal concerning the use of the Hybrid III in FMVSS 208; February, 1984

[5] Mertz, H.J. and Patrick, L.M., "Strength and Response of the Human Neck", Fifteenth Stapp Car Crash Conference; SAE paper number 710855; 1971.

[6] Obergefell, L.A., Ma, D., Rizer, A.L.,"Dynamic Modeling and Rollover Simulations for Evaluation of Vehicle Glazing Materials", SAE technical paper number 950050, 1995

moving in the same direction at about 96 kmph on a four lane highway. The passenger car made a change to the center lane, where the pickup truck was traveling, and its left rear hit the right front of the pickup. Because of this collision, the pickup made a sharp maneuver, initiating a rollover coupled with a yaw rotation. The pick-up truck experienced three complete rolls before it came to rest. The belted driver occupant hit the side window glazing. The vehicle motion and interior data from the ATB model were transformed to set up an equivalent MADYMO simulation. The ATB simulations were run with a belted driver only to examine its interaction with tempered glass, rigid plastic and laminated safety glass. The MADYMO simulations were set up to further study the motion of an unbelted driver occupant during the rollover crash and estimate the injury potential and retention capabilities of bilaminate glass-plastic glazing. For this case, the vehicle handling motion was already available and it was not necessary to recreate it using the VDANL program. The parametric simulation runs shown in Table 6.1, were set up with a 50th percentile Hybrid III dummy seated on the driver seat. The results from the simulations are discussed in the following sections.

6.2.1 Results from the Restrained Driver Occupant Simulations

For the restrained driver, significant contacts of head and shoulder with the left front glazing were identified at a later time step in the simulations (around 2000 msec). There was a series of minor contacts of the dummy's head, left shoulder and left upper arm with the glazing before the severe head contact occurred. Due to these contacts, the dummy's velocity and orientation were changed for different glazing materials. In all the simulations, the dummy moved to the left as the vehicle made its first quarter roll. The resultant relative velocity of the dummy's head in this first impact with the glazing was about 5 kmph, which was not enough to break the tempered glass. The occupant impact velocity seemed to increase in the subsequent impacts as the vehicle made two complete rolls. The maximum relative velocities of the head and upper torso at impact with glazing were 20 kmph and 7 kmph, respectively. The lap belt kept the dummy close to the seat. The shoulder belt pulled the dummy towards the left as the vehicle made its 5th quarter roll to land on the driver side. The significant head contact of the dummy with the glazing occurred at that time. The dummy's head, left shoulder and left upper arm contacted the glazing. The maximum force was transferred to the glazing by the head, impacting it near the upper right corner close to the Bpillar. The results from the simulations are tabulated in Table 6.3.

Table 6.3 Toyota pickup rollover - results from restrained Hybrid III driver occupant simulations.

	Open	Tempered	PMMI	Jeep Winds	Dupont
HIC	78	200	276	369	217
Neck Comp. (N)	369	2413(glazing)	1994(glazing)	2256(glazing)	2927(glazing)
Neck Tension (N)	925	1104	1192	1134	1072
Moment X (Nm)	-27	-30	-25	45	32
Moment Y (Nm) *	21/-29	25/-36	23/-34	30/-33	23/-34
Moment Z (Nm)	27	12	9.7	11	11
Result H Acc (G's)	29	94	87	122	108
Retention	**fail**	**fail**	pass	pass	pass
Velocity (kmph)	head = 20	head=20, upper torso = 7			
Head impact	none	left front glazing			
Glazing Impact	none	left upper arm, left shoulder, head, face and chin			

* Neck Flexion / Extension Bending moments

The HIC values obtained from the simulations without glazing, and with different types of glazings were insignificant. These HIC values do not indicate a potential for severe head injury. The severity of neck injury was estimated by comparing the maximum neck loads and moments with the Mertz's reference values. The maximum axial compression loads on the neck for tempered glass, rigid plastic and safety glass glazings, were well below the critical value specified in the injury assessment reference by Mertz. The maximum axial compression load on the neck was highest for the DuPont glass-plastic glazing. However, the compression load was still below the critical value and may not produce severe neck injury. The tension load was inflicted on the neck after the head rebounded from severe impact with the glazing (2000 msec). Again, the neck tension loads were below the critical values defined by Mertz for all the glazing simulations. The neck flexion bending moment and neck extension bending moment values were also less than the

Mertz's critical values for all the glazing simulations.

The maximum values obtained from the simulations were compared with the HIC 1000, Mertz's criteria for neck injury and occupant retention. For each criteria, the glazing performance was categorized as pass or fail. The injury values are printed in bold numbers in the table for glazings that failed the performance test. The results indicate that 'no glazing' [rolled down window or shattered tempered glass] and tempered glass glazing will allow partial ejection of a belted dummy. The plastic and glass-plastic glazing will retain the belted dummy without causing a severe injury.

6.2.2 Results from the Unrestrained Driver Occupant Simulations

The unrestrained driver dummy moved more vigorously in the vehicle during the rollover. The dummy's head contacted the front header, windshield, roof and front left side glazing. The most severe contacts of the head occurred with the windshield and roof. The dummy's head, lower torso, left upper arm, and left shoulder contacted the left front side window glazing. The maximum load of the dummy was transferred to the glazing by the lower torso contact. The maximum resultant relative velocity of the head and upper torso were 20 kmph and 16 kmph, respectively. There was a series of minor contacts of the dummy with the glazing before the severe head contact occurred; hence, the maximum injury values are different for the simulations with different glazings. The results from the simulations are tabulated in Table 6.4.

Table 6.4 Toyota pickup rollover - results from unrestrained driver occupant simulations.

	Open	Tempered	PMMI	Jeep	Dupont
HIC	**Ejection**	303	439	727	214
Neck Comp. (N)	**Ejection**	**6086 (header)** 500 (glazing)	**5915 (header)** 1000 (glazing)	**6086 (header)** 1500 (glazing)	**5924(header)** 500 (glazing)
Neck Tension (N)	**Ejection**	774	1285	1559	611
Moment X (Nm)	**Ejection**	131	-222	-98	125
Moment Y (Nm) *	**Ejection**	110/-**59**	117/-**76**	115/-**69**	97/-**66**
Moment Z (Nm)	**Ejection**	-53	-50	-105	-70
Result H Acc (G's)	**Ejection**	83	104	119	72
Retention	**fail**	**fail**	pass	pass	pass
velocity (kmph)	**head = 5**	h=20, upper torso = 16			
Head impact	**none**	left side header, left front window, roof, windshield			
Glazing Impact	**none**	lower torso, left upper arm, left shoulder, head			

* Neck Flexion / Extension Bending moments
* Bold numbers represent failed performance criteria

All the simulations regardless of glazing type, produced moderate HIC values which corresponded to the head contact with the roof. The axial compression load on the neck was higher than the Mertz's critical value for all the simulations. However, neck compression load was received from the roof and front header contacts. The plastic and glass-plastic glazings themselves did not cause any major injury to the dummy from direct contact and prevented ejection. In the simulation with the open window the unbelted dummy came out of the vehicle in the first quarter roll. There were no major contacts of the dummy with the interior of the vehicle before ejection. All other glazings retained the dummy inside the vehicle.

The results indicated that the open window allowed occupant ejection in the first quarter roll of the vehicle. The tempered glass glazing broke due to the lower torso impact at 2590 msec. The rigid plastic, safety glass and glass-plastic glazings retained the unbelted dummy in the vehicle. The ejection mitigating glazings did not reduce the injuries to the dummy that were inflicted by the windshield and roof. However, these glazings did not contribute to any new severe injuries to the dummy from the direct contacts. They prevented ejection, thus reducing chances of inflicting fatal injury to the dummy by external sources.

6.3. Rollover of a Toyota Corolla (CASE # 106 K, PSU # 11, Year 1992)

A 1986 Toyota Corolla was moving southbound at about 96 kmph on a gravel road [7]. The driver lost control of the vehicle and ran off the right side of the road. The vehicle rolled six quarter turns and ended up on its roof. There were four occupants in the vehicle. The belted driver was retained in the vehicle with AIS 2 injury. The unrestrained front passenger (a small teenager) was ejected from the vehicle through the front right side window. He received AIS 1 abrasion and laceration injuries to the head from windshield and sun visor contacts. He also received AIS 2 concussion injury to the head from the sun visor. After the ejection the occupant received AIS 1 abrasions on the back from dragging against the concrete. The rear left seat passenger was ejected from the rear left side window. The data on the rear right side passenger was marked unknown in the NASS file.

For the baseline run, simulations were set up to predict the kinematics of the unrestrained front passenger. The vehicle motion was reconstructed in two parts. First, the vehicle maneuvering was simulated in VDANL software to obtain the linear and angular velocity of the vehicle at the onset of rollover. Then, a lumped mass model of the vehicle was created in MADYMO and its linear and angular motions were simulated as it interacted with the ground.

The accident collision diagram of the rollover crash showed that the driver steered the vehicle sharply to the left after it ran off the right side of the road. The vehicle lost its stability due to this maneuvering and started to roll. The initial velocity (95 kmph) and change in steering angle (2 radians) with time were entered in the VDANL program for the vehicle model of the Toyota Corolla. A number of simulations were run by changing the steering rate until the vehicle

[7] NASS report, PSU # 11, Case # 106K, Year 1992

trajectory in the simulation matched the NASS report. This trajectory also lead to vehicle instability and the vehicle started to roll at a rate of 3.2 rad/s and with a yaw rate of 0.478 rad/s. The longitudinal and lateral velocities of the vehicle at this point were 78 kmph and 11.3 kmph, respectively.

A single segment MADYMO model of the vehicle was created. The inertial properties and exterior dimensions of the vehicle were obtained from the MVMA specifications and VDANL data sets. Contact ellipsoids were used to model the roof, bumper, and tire of the vehicle. The angular and linear motions of the vehicle obtained from the VDANL program were used to drive the MADYMO model. A number of simulations were run by changing the force deflection properties and energy absorption coefficients for the vehicle and ground contacts, until the number of rolls and final position of the vehicle in the simulation matched that in NASS case.

A MADYMO model of the vehicle interior and a 5th percentile female dummy was created to simulate the kinematics of the occupant as it interacted with the interior of the rolling vehicle. The linear and angular motions of the vehicle obtained from the vehicle model were used to drive the occupant model. The NASS file indicated that the windows of the vehicle were shattered due to the ground contact. Hence, no glazing was used in the baseline simulation. The unbelted passenger made contact with the belted driver. An ellipsoid was placed on the driver seat to model the belted driver. The occupant motion was defined relative to the vehicle. At the start of roll, the velocity of the vehicle was reduced to 78 kmph from the initial velocity of 95 kmph. Assuming that the unrestrained occupant will move forward with the same velocity as the initial velocity of the vehicle, the occupant was given a forward velocity of about 15 kmph relative to the vehicle. This forward relative velocity depends on the braking and avoidance maneuver of the vehicle and could not be accurately computed from the available NASS data.

The simulations were also set up by replacing the 5th percentile female dummy with a 50th percentile Hybrid III dummy seated on the front passenger seat. All other parameters including the motion of the vehicle were unchanged. These simulations were set up to predict the motion of a mid size occupant in the rolling vehicle. The results from the two sets of simulations are discussed in the following sections.

6.3.1 Results from Unrestrained 5th Percentile Female Front Passenger Occupant Simulations

The baseline simulation was run to match the occupant motion with the actual crash. The NASS report indicated the occupant's head contacted the windshield, front header, and Apillar before being ejected from the vehicle. The dummy's contacts with the vehicle interior in the simulation were matched with that in the actual crash. The unbelted dummy moved forward and then to the right and made contacts with the windshield, and Apillar. As the vehicle continued to roll, the dummy's head contacted the roof. The dummy was ejected from the vehicle at the sixth quarter turn. The axial neck compression load (3372 N for 10 msec) due the windshield contact was higher than the Mertz's reference value and it occurred before the ejection. The NASS report did not show any serious neck injury. The critical neck injury predicted in the simulation was due to the dummy's motion in the forward direction which resulted in a severe impact with the windshield. As stated earlier the relative motion of occupant in the forward direction could not be computed accurately from the available NASS data.

Due to the low severity of this accident, the simulations with different glazings showed no significant difference in the kinematics and dynamic responses of the dummy. The maximum values for the injury criteria were nearly the same for all the simulations with or without glazing. The neck compression loads inflicted by the windshield, roof, and Apillar contacts were higher than the Mertz's critical values. These contacts resulted from the relative forward motion of the dummy and occurred before any contact with the glazing was made. The dummy's head, face, and chin contacted the front right side glazing. These contacts were not as significant as compared to contacts with windshield, roof and Apillar. All the glazings, including the tempered glass, prevented dummy ejection without inflicting any additional injury by direct contact. The contact forces between the dummy and tempered glass were not enough to break the glazing.

The maximum relative velocity of the head at the impact with the side glazing was 15 kmph.

6.3.2 Results from Restrained 5th Percentile Female Front Passenger Occupant

The simulations for the 5th percentile female passenger were repeated after restraining the dummy with a three-point belt system. The three-point belt system kept the dummy from hitting the roof and windshield and prevented complete ejection. In the simulation with no glazing, the dummy was partially ejected with a head relative resultant velocity of 14 kmph. In the simulations with glazing, the dummy's head, right shoulder and right upper arm contacted the right front side glazing. The maximum relative velocity of the head at the impact with the glazing was 14 kmph. The relative resultant velocity of the upper torso was 7 kmph. The maximum load was transferred to the glazing by the head contact at the upper right corner of the glazing near the Bpillar, which occurred at about 1800 msec. The results from the simulations are tabulated in Table 6.5.

Table 6.5: Toyota Corolla rollover - results from restrained 5th percentile female passenger occupant simulations

	Open	Tempered	PMMI	Jeep	Dupont
HIC	13	259	156	307	342
Neck Comp. (N)	276	2119(glazing)	1021(glazing)	2052(glazing)	1781(glazing)
Neck Tension (N)	437	629	508	613	680
H Acc (G's)	17	93	56	100	104
Retention	**fail**	pass	pass	pass	pass
Velocity (kmph)	head = 14	head=14, upper torso = 7			
Glazing Impact	none	right upper arm, right shoulder, head			
Head impact	none	right front glazing			

The HIC values obtained from these simulations were not significant and may not cause a severe head injury. The axial neck compression and tension loads were below the Mertz's reference values for all the glazing simulations. The results showed that the window without glazing allowed partial ejection of the dummy. All the glazings including tempered glass retained the dummy completely. The relative velocity of the head at the impact with the glazing was 14 kmph. No serious injury was caused to the neck and head by the direct impact with the glazing.

6.3.3 Results from Unrestrained Hybrid III Front Passenger Occupant Simulations

To study the motion of a mid-size occupant in the same rollover, the 5th percentile female dummy seated in the front passenger seat was replaced with a 50th percentile Hybrid III dummy. The unbelted Hybrid III passenger dummy moved more vigorously in the vehicle during rollover. The dummy moved forward and then to the side toward the right front window. In the simulation with no glazing, the unrestrained Hybrid III dummy was ejected from the right front window of the vehicle at the sixth quarter turn. The lower torso of the dummy came out first followed by the upper torso and head. The dummy’s head made contact with the front header, windshield, Apillar, roof and top of the instrument panel. It received critical neck loads from the windshield and top of the instrument panel contacts before the ejection. Again, these neck loads were due to the dummy’s motion in the forward direction and occurred before or at the onset of the rollover. The maximum relative velocity of the head at the impact with windshield was 18 kmph. The results are tabulated in Table 6.6.

Table 6.6 Toyota Corolla rollover - results from unrestrained Hybrid III passenger occupant simulations

	Open	Tempered	PMMI	Jeep	Dupont
HIC	277	295	155	166	262
Neck Comp. (N)	**3197**	**6628(windshield)**	**6084(windshield)**	**6114(windshield)**	**5980(windshield)**
Neck Tension (N)	2372	2357	2357	2357	2357
Moment X (Nm)	177	69	53	54	57
Moment Y (Nm) *	131/-**69**	130/-**77**	130/-**69**	130/-**69**	130/-**69**
Moment Z (Nm)	48	48	48	48	48
Head Acc (G's)	113	125	84	104	125
Retention	**fail**	**fail**	pass	pass	pass
Velocity (kmph)	head =13	head=13, upper torso = 10			
Glazing Impact	none	right upper arm, right shoulder, lower torso			
Head impact	Front header, A pillar, roof, windshield, top instrument panel				

* Neck Flexion / Extension Bending moments

* Bold numbers represent failed performance criteria

In the simulations with glazing, the lower torso, right upper arm and right shoulder impacted the glazing. The dummy's head made contact with the front header, windshield, Apillar, roof and top of the instrument panel but did not make any contact with the side glazing. In the simulation with the tempered glass, the front right side glazing broke due to shoulder impact at about 1400 msec. The impact force from the lower torso was also high enough to break the tempered glass. The neck compression loads and extension bending moments inflicted by the windshield and top of the instrument panel exceeded the Mertz's reference values. The value of the axial compression load on the neck varied in simulations with different glazings. The severe impact with the windshield occurred after the dummy impact with the side glazing. In simulations with plastic, safety glass and glass-plastic glazings, the dummy rebounded from the glazing impact and hit the windshield and top of the instrument panel, receiving critical neck injuries. The HIC was not significant and the value corresponded to the head contact with the windshield. The rigid plastic, laminated safety glass and glass-plastic glazings retained the dummy in the vehicle. Critical neck loads were received by the dummy after it rebounded from the side glazing impact and contacted the windshield. However, no severe injury was received by the dummy from the direct contact with the side glazing.

6.3.4 Results from Restrained Hybrid III Front Passenger Occupant Simulations

A three-point belt system kept the Hybrid III dummy close to the seat and prevented complete ejection from the front windows with no glazing. However, the dummy's head was partially ejected with a relative velocity of 15 kmph. In the simulations with the glazings, the dummy's head, right lower arm, right upper arm, and right shoulder contacted the glazing. The dummy's head also made contact with the right door header and roof. The maximum resultant relative velocity of the head and upper torso at the impact with the glazing were 13 kmph and 9 kmph, respectively. The right upper arm and right shoulder transferred the maximum load to the glazing. The head made only minor contact with the glazing. The results are tabulated in Table 6.7.

Table 6.7 Toyota Corolla rollover - results from restrained Hybrid III passenger occupant simulations

	Open	Tempered	PMMI	Jeep	Dupont
HIC	21	185	51	41	38
Neck Comp. (N)	1648	2090(glazing)	1466(glazing)	1757(roof)	1447(roof)
Neck Tension (N)	508	1377	813	823	859
Moment X(Nm)	32	-47	-55	-49	-53
Moment Y(Nm) *	36/-21	38/-15	38/-15	38/-15	38/-15
Moment Z (Nm)	-8	-19	-16	-14	-14
Head Acc (G's)	21	99	27	34	28
Retention	**fail**	**fail**	pass	pass	pass
Velocity (kmph)	head = 15	head=15, upper torso = 11			
Glazing Impact	none	right upper arm, right shoulder			
Head impact	roof	roof and (or) glazing			

* Neck Flexion / Extension Bending moments

The HIC was insignificant in all the glazing simulations and was due to the head impact with the roof. The maximum axial compression and tensile loads on the neck were lower than the critical values. The neck moments were also less than the critical values for all glazing simulations. The simulation with no glazing produced partial ejection of the dummy. The tempered glass failed due to right shoulder, right upper arm and head impacts. The rigid plastic, laminated safety glass and glass-plastic glazings did not produce any serious injury to the dummy by direct contact and prevented the partial ejection.

6.4. Rollover of a 1985 Volkswagen Jetta (NASS case # 147B, PSU # 02, Year 1992)

A 1985 Volkswagen Jetta was moving northbound on a two lane highway at about 88 kmph. The driver of the vehicle fell asleep and the vehicle left the road to the right, striking a rock embankment. The vehicle overturned in the driving lane making four quarter turns. The belted driver survived with an AIS 2 injuries. The unrestrained front passenger (size of a 50th percentile Hybrid III dummy) of the vehicle was ejected from the right front window and was killed. He received an AIS 2 fracture injury to the head from right Apillar impact prior to ejection. In addition he suffered fatal head injury possibly due to the ground contact. The vehicle's side glazings were disintegrated by the impact forces. The windshield was cracked by the occupant contact. The NASS file identified the head contacts with the windshield, right Apillar and instrument panel before the ejection [8].

For the baseline run, simulations were set up to predict the kinematics of an unrestrained front seat passenger ejected through the disintegrated right front window. Since the glazing was disintegrated due to the ground impact prior to occupant ejection, the occupant glazing contacts were not modeled. An approach similar to that described in section 5.3 for the Toyota Corolla rollover was followed to obtain the linear and angular motions of the vehicle which closely matched the vehicle trajectory described in the NASS file. The information on the vehicle linear

[8] NASS report, PSU # 02, Case # 147, Year 1992

velocity, steering maneuver and number of quarter rolls in the complete rollover, was used to describe the vehicle motion in the simulation. The impact of the vehicle with the rock embankment was ignored in the VDANL simulation.

A MADYMO model of the vehicle interior and an unbelted 50th percentile Hybrid III dummy, seated at the front passenger side, was created. The linear and angular motions of the rolling vehicle obtained from the MADYMO vehicle model were used to drive the occupant model. The parametric simulations discussed in section 6.2 were carried out. The same set of simulations were repeated after restraining the dummy with a three point belt system. The results from two sets of simulations are discussed in the following sections.

6.4.1 Results from Unrestrained Hybrid III Front Passenger Occupant Simulations

A baseline simulation was run to match the dummy's motion with that in the actual crash. The dummy moved forward and made contact with the instrument panel and windshield. As the vehicle continued to roll the dummy's head made contacts with the Apillar and roof [Figure 6.4]. The dummy was ejected from the vehicle at the fourth quarter roll. The maximum axial neck compression load due to the windshield contact was higher than the Mertz's reference value and it occurred before the ejection. The results are tabulated in Table 6.8.

Table 6.8 Volkswagen Jetta rollover - results from unrestrained Hybrid III passenger occupant simulations

	Open	Tempered	PMMI	Jeep	Dupont
HIC	197	414	171	233	269
Neck Comp. (N)	**3416(windshield)**	**3416(windshield)** 500(glazing)	**3416(windshield)** 800(glazing)	**3416(windshield)** 800(glazing)	**3416(windshield)** 1000(glazing)
Neck Tension (N)	821	1271	399	326	368
Moment X (Nm)	108	108	108	108	108
Moment Y (Nm) *	84/-**90**	84/-**90**	84/-**90**	84/-**90**	84/-**90**
Moment Z (Nm)	68	68	68	68	68
Head Acc (G's)	75	111	73	88	121
Retention	**fail**	**fail**	pass	pass	pass
Velocity (kmph)	head = 22	head=18, upper torso = 16			
Glazing Impact	none	upper torso, right upper arm, right shoulder, head			
Head impact	windshield, front header, right door header, roof				

* Neck Flexion / Extension Bending moments

* Bold numbers represent failed performance criteria

In the simulations with the glazing, the dummy's head impacted the windshield, right door header, roof, and front right side window glazing [Figure 6.5]. The dummy's upper torso, right upper arm, right shoulder, and head impacted the front right side glazing. The right upper arm and right shoulder transferred the maximum load to the glazing. The maximum relative velocity of the head and upper torso at the impact with the side glazing were 22 kmph and 18 kmph, respectively. Moderate HIC values were produced in all the glazing simulations. The time interval for HIC computation corresponded to the head contact with the right door header in all the glazing simulations. These HIC values may not cause any severe injury to the head. The maximum neck compression loads, inflicted by the windshield contact, were the same for all the glazing simulations and were greater than the critical values. These contacts occurred before any major dummy contact with the side glazing. The neck injury received by the direct contact with the side glazing was not significant. The axial neck tensile load and flexion bending moment on the neck were well below the critical values for all the glazing simulations.

The dummy was ejected completely in the simulation with no glazing. The tempered glass failed due to right upper arm and right shoulder impacts. The rigid plastic, laminated safety glass and glass-plastic glazings retained the dummy in the vehicle without attributing any new injury to the dummy by direct contacts.

6.4.2 Results from Restrained Hybrid III Passenger Occupant Simulations

The three-point belt system kept the Hybrid III dummy close to the seat and prevented complete ejection [Figure 6.5]. The dummy moved forward and then to the right. The dummy was ejected partially in the simulation with no glazing with a relative head velocity of 14 kmph. The head contacted the roof as the vehicle rolled onto its roof. The results are tabulated in Table 6.9.

Table 6.9 Volkswagen Jetta rollover - results from restrained Hybrid III passenger occupant simulations

	Open	Tempered	PMMI	Jeep	Dupont
HIC	66	98	191	340	249
Neck Comp. (N)	3222(roof)	3222(roof) 250(glazing)	3222(roof) 1000(glazing)	3222(roof) 1500(glazing)	3222(roof) 500(glazing)
Neck Tension. (N)	1099	1099	1099	1099	1099
Moment X(Nm)	35	-40	-44	-42	-43
Moment Y(Nm) *	75/-25	75/-25	75/-25	75/-25	75/-25
Moment Z (Nm)	-9.8	10.9	6	6	6
H Acc (G's)	36	70	56	94	99
Retention	**fail**	**fail**	pass	pass	pass
Velocity (kmph)	head = 14	head=14, upper torso = 10			
Glazing Impact	none	right upper arm, right shoulder, head			
Head impact	roof	roof, right front glazing			

* Neck Flexion / Extension Bending moments

In simulations with the glazing, the dummy's right upper arm, right shoulder and head contacted the glazing. However, these contacts were not significant enough to produce severe injury to the neck and head. The right upper arm and right shoulder transferred the maximum load to the glazing. The relative velocities of the head and upper torso at the impact with glazing were 13 kmph and 10 kmph. The HIC was insignificant in all the simulations. The maximum axial compression load on the neck was caused by the head contact with the roof which occurred before any contact with the glazing was made. The maximum axial compression load on the neck inflicted by the roof contact (3222 N) was same for all the glazing simulations. The compression load was within the limit of Mertz's reference value. The axial compression and tension load inflicted by the glazing contact were also below the critical values. The neck flexion and extension moments were well below the critical value for all the glazing simulations.

The results showed that the window without the glazing allowed partial ejection of the dummy. The tempered glass glazing failed due to the right upper arm and shoulder impact. The plastic, safety glass, and glass-plastic glazing prevented the partial ejection of the dummy without causing any critical injury to the neck and head.

6.5 Discussion and Conclusions

The simulations presented in this report do not represent the rigorous analysis of all or typical rollover crashes but present some quick insight into the potential capabilities of alternative glazings. The performance of the alternative glazing were estimated in terms of occupant retention and injury potential.

In simulations with a restrained dummy, the dummy's head, shoulder and upper arm made contact with the glazing. All the glazings except the tempered glass appear to have sufficient strength characteristics to prevent partial ejection of the dummy. The mounting configuration was ignored for defining the force deflection characteristics of the glazings. The alternative glazings did not cause any severe neck and head injury to the dummy from the direct contacts and prevented partial ejection.

In the simulations with an unrestrained dummy, the dummy's lower torso, upper torso, head, shoulder and upper arm made contact with the glazing. The dummy's head also made contact with the windshield, front header, side window header, roof, Apillar, and instrument panel. In all the simulations with the unrestrained dummy, the glazing impacts appeared to be less injurious than the impacts with the other interior components. The rigid plastic, laminated safety glass and glass-plastic glazings prevented the dummy ejection without attributing to any new severe injury to the dummy from the direct glazing contacts.

The relative velocity of the head at the impact with the glazing varied from 14 kmph to 20 kmph. The relative velocity of the upper torso at the impact with the glazing varied from 7 kmph to 14 kmph.

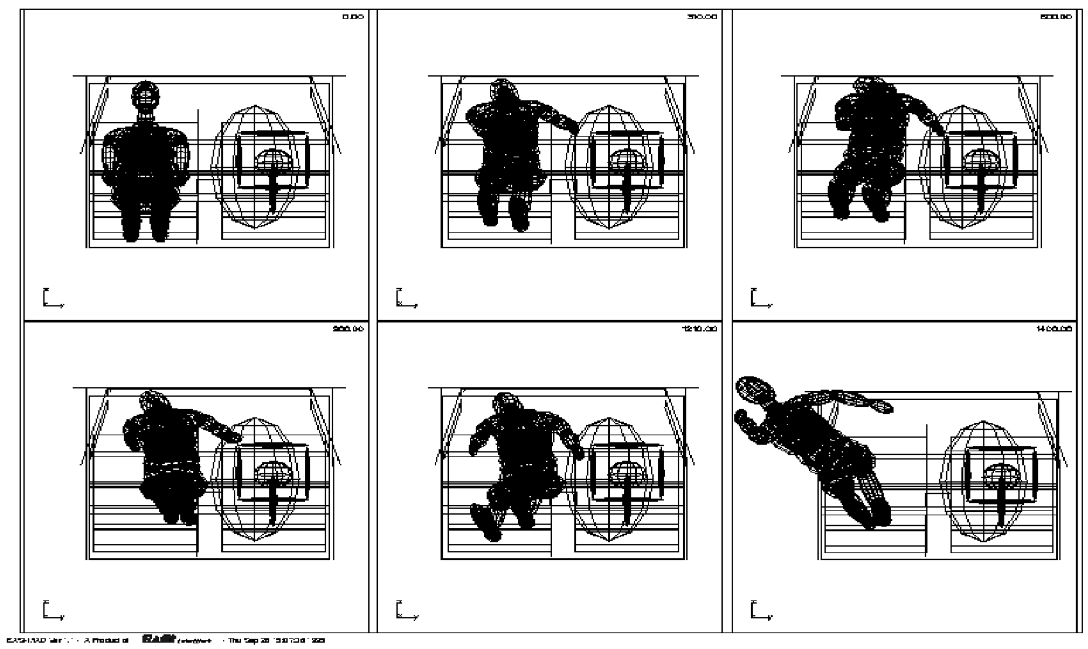


Figure 6.3 Occupant simulation of an unrestrained Hybrid III passenger with no glazing window in a rollover crash.

7. COMPONENT TEST DEVELOPMENT

The National Highway Traffic Safety Administration is conducting research to reduce the number of occupant ejections through the side door windows. This section describes the results of the Advanced Glazing Research Team's research, to date, on developing a component test procedure for improved side glazing.

Efforts have concentrated on the first two tasks of this program. The first task is to establish the general impact conditions, that is, impactor mass and velocity. The selection of the target energy values is crucial, as they will determine the strength required of the side glazings. The stronger the glazing, the higher its retention capability, but the higher its potential for producing head and perhaps neck injuries. The second task is the development of the necessary equipment and initial testing of the advanced glazing systems, to determine their potential for mitigating occupant ejection. The information gained in this task will be incorporated in the next task, which is to establish performance criteria. Full system testing is used to decide what criteria must be addressed in the component test such as retention capability, head injury potential, neck injury potential, laceration potential, and what type of measurement must be made during a test in order to evaluate the different criteria.

7.1 Initial Impact Velocity Assessment

Two sources of data were used to determine the impact velocity during both side impact and rollover accidents. First, high speed film analysis of rollover tests were conducted to measure occupant to glazing contact speeds[1,2]. In these tests, it was found that the shoulder made contact with the glazings at speeds ranging from 2.5 kmph (1.6 mph) to 31.3 kmph (19.5 mph), averaging 11.3 kmph (7.0 mph). Also in these tests, the heads made contact with the side roof rails.

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[1] NHTSA Memorandum from Stephen Summers to Distribution, Dated April 30, 1993.

[2] Knapton, D., "Rollover Crash Test Film Analysis", NHTSA Report DOT-TSC-HS-476-PM-83-25, July 1983.

Next, NASS accident data were analyzed for vehicle lateral change in velocity (Δv) in crashes involving side glazing disintegration due to occupant contact[3]. These Δv's ranged from 0 to 56.3 kmph (35.0 mph), averaging 17.8 kmph (11.1 mph). The single most frequent contact speed was about 30 kmph (19 mph), accounting for over 20% of all cases examined. Kinematically, in a typical FMVSS 214-type side impact, the door is crushed inward by the striking vehicle, hitting the upright seated occupant. Door to thorax contact is made, generally followed by excursion of the head through the side window opening (current tempered side windows shatter immediately upon striking vehicle impact). Camera positions in these crash tests are not adequate for estimating head to window opening speeds, although door to thorax contact speeds are frequently about 40 kmph (25 mph).

7.2 Effective Mass Measurement

There were several steps taken to determine the impactor mass. The steps involved a number of impact tests conducted under various conditions, and computer modeling to augment the findings of these tests. The following sections describe this research.

7.2.1 Pendulum Impact Testing

A series of pendulum impact tests were conducted on a BioSID Anthropomorphic Test Device to measure effective mass of the head and shoulder. The BioSID was chosen because it is configured for side impact, unlike the Hybrid-III dummy, and has a shoulder which is not present in the SID dummy. A linear impact pendulum weighing 23.4 kg (51.5 lb) was used in all tests. The head and shoulder were struck laterally in separate tests, using two impact speeds and four impact surfaces (see Table 7.1). In addition to the rigid impactor face, three types of padding were added to the impactor face to increase the contact time inherent in glass-plastic glazing impacts.

[3] NHTSA Memorandum from Stephen Summers to Distribution, Dated April 30, 1993.

Table 7.1 Pendulum Test Matrix

Body Region	Impact Speed *kmph (mph)*	Impactor Face			
		Rigid	Arsan 106.9 kPa (15.5 psi)	Ethafoam 120.0 kPa (17.4 psi)	Arcel 196.5 kPa (28.5 psi)
Head	9.7 (6.0)	02,03	07	05	09,10
	12.9 (8.0)	04	08	06	11
Shoulder	9.7 (6.0)	18	16	14	12
	12.9 (8.0)	no test	17	15	13

For each head impact, tri-axial accelerations of the head center of gravity and the impactor acceleration were measured. From these measurements, head resultant acceleration and impact force

were directly calculated. Dividing the force time history by the acceleration time history yields the effective mass time history. As expected, head effective mass was about 4.5 kg (10 lb), the weight of the head, early in the event (ie. first 10-15 msec), before the weight of the body could have an effect. The effective mass then rose to a value between about 10 kg (22 lb) to 18 kg (40 lb), depending on the impact condition. Since faster and/or softer impact surface conditions produced a longer period of contact between the impactor and head, thereby increasing the effect of the body weight, these tests rose to higher effective mass values. Example time histories are shown in Figures 7.1 and 7.2.

For each shoulder impact, shoulder, upper spine (T01), and impactor accelerations were measured. The shoulder accelerations were very oscillatory, due to the low mass of the BioSID shoulder, so T01 accelerations were used for the effective mass calculations. Unfortunately, since T01 is somewhat remote from the impact location, its response lags that of the impactor. This results in a near zero-divide situation, causing an artificially high spike early in the effective mass time history (about the first 10 msec). An example set of plots from one test is shown in Figure 7.3. Typically, the effective mass settles down to about 16 to 18 kg (35 to 40 lb) after the initial spike. It then rises gradually over the next 20 msec or so, to about 25 to 27 kg (55 to 60 lb). At that time, it rises sharply to between 60 and 85 kg (130 and 185 lb), depending on the impact speed and impactor surface.

The head impacts produced two significant findings. First, the procedure for calculating effective mass was validated in that the resulting effective mass early in the event was essentially the weight of the head. Second, the effect of the upper torso and neck was evident after only 10 or 15 msec, so that head and shoulder impacts should not be considered separate events beyond that time. From the shoulder impacts, the upper torso effective mass was measured to be about 16 to 18 kg (35 to 40 lb) initially. At this point in the event, the mass of the head presumably was partially affecting this value. Therefore, a lower bound of 16 kg (35 lb) seems reasonable. The effective mass raises to about 25 to 27 kg (55 to 60 lb) over the next 20 msec. By that time in the event, the mass of the head is probably completely represented in that value. Therefore, an upper bound of 27 kg (60 lb) seems reasonable.

7.2.2 HYGE Sled Testing

The pendulum tests indicated that the effective mass of a head/shoulder impact is likely between 16 and 27 kg (35 and 60 lb). This is for an impact that was isolated to those areas, that is, none of the impact was absorbed by lower portions of the body. To explore this effect, a series of six HYGE sled tests were run, also using the BioSID.

The sled buck was similar to the standard side impact sled buck used extensively in side impact research. Its main components are a 'door', which consists of three rigid load plates covered with 76 mm (3 in) of Ethafoam LC 200 padding. This padding, when mounted to a rigid wall, was previously identified as producing the 'optimal' stiffness for side impact thoracic protection[4]. Two

[4] Zuby, D. S., “Evaluation of the BioSID and the EuroSID-1: Volume I - Padded Wall Comparison Tests -- BioSID, EuroSID and SID”, NHTSA Report DOT-HS-807-807, July 1991.

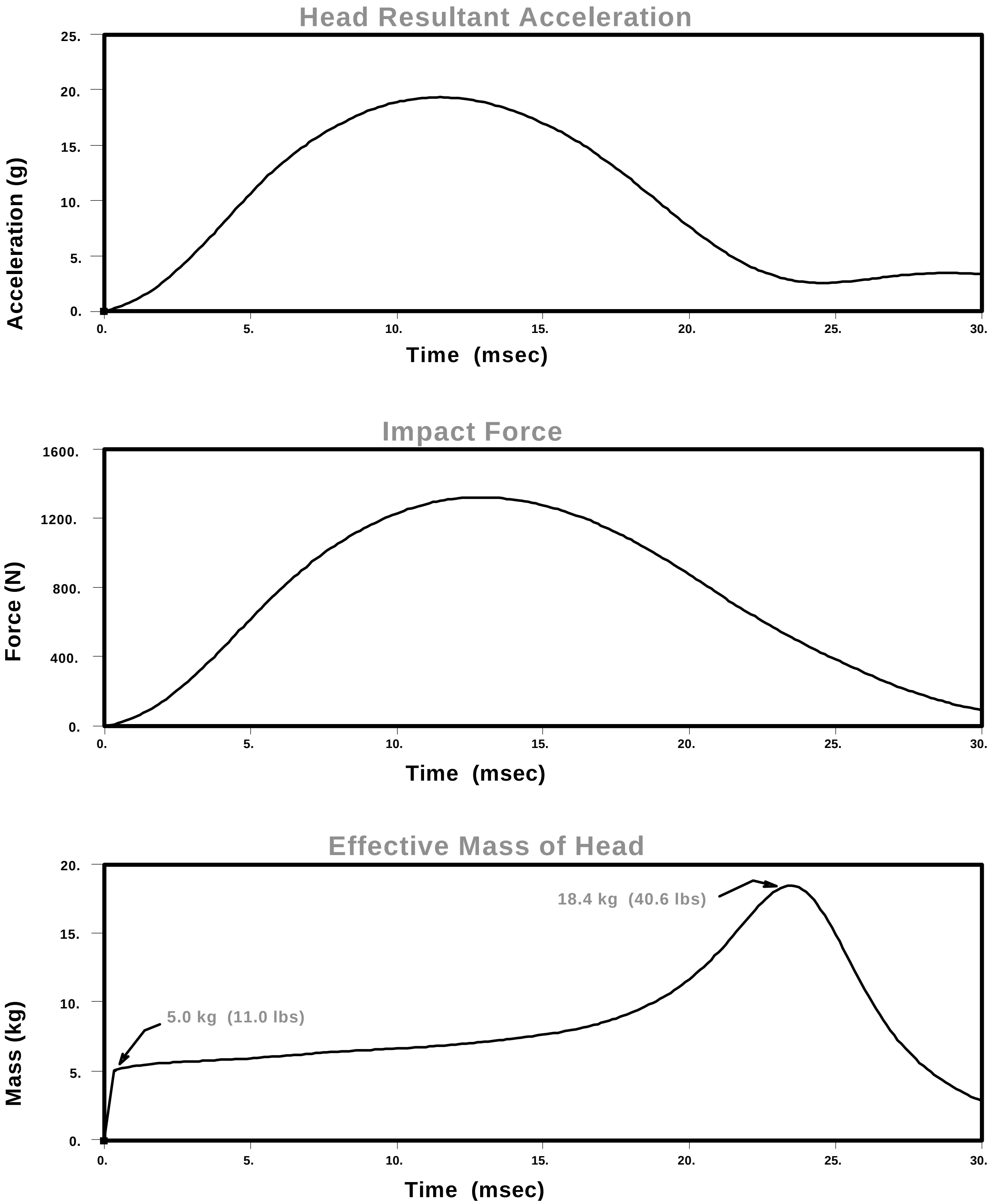


Figure 7.1 Head Effective Mass Result from 2.7 m/s Pendulum Impact with Arsan Foam

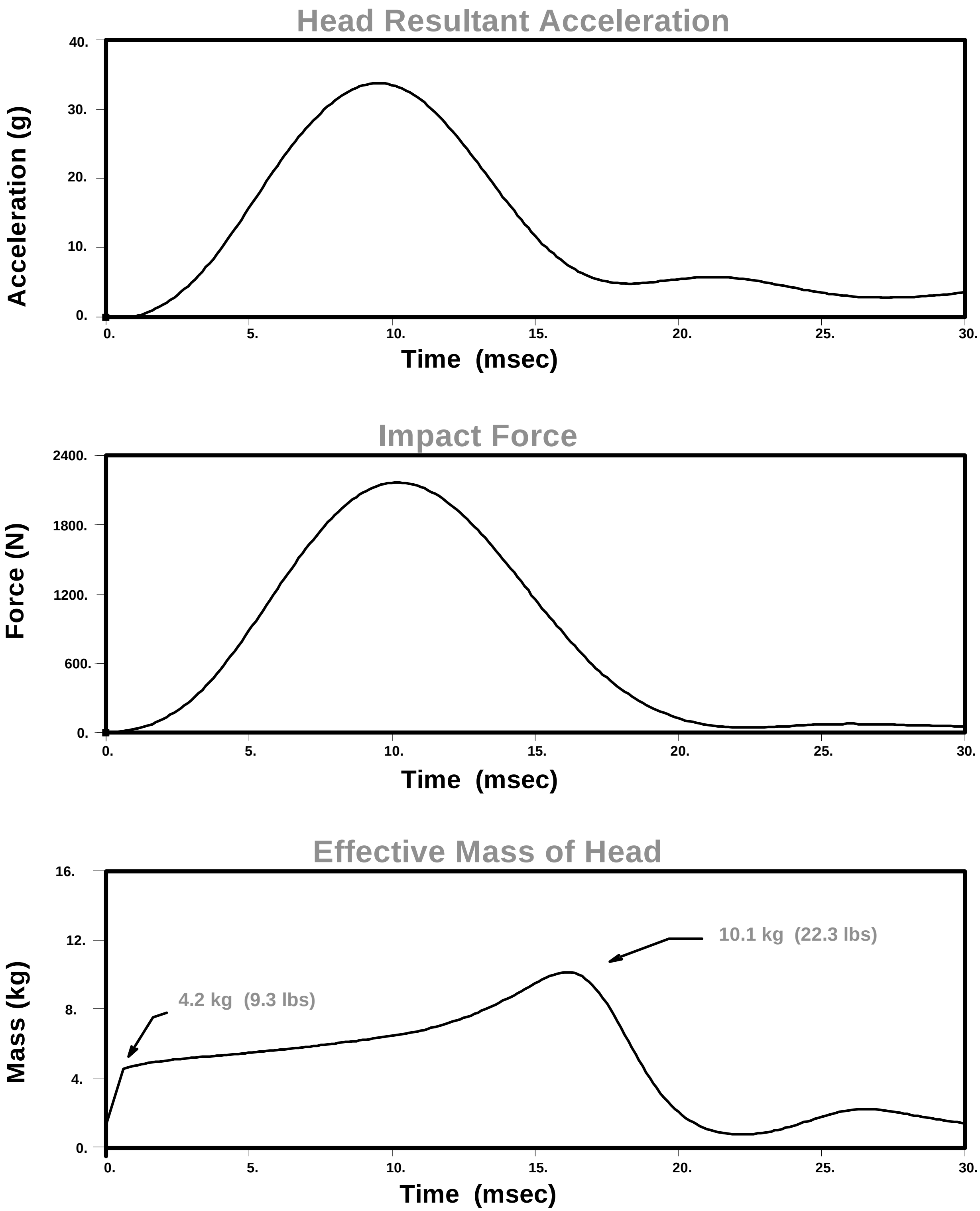


Figure 7.2 Head Effective Mass Result from 2.7 m/s Pendulum Impact with Arcel Foam

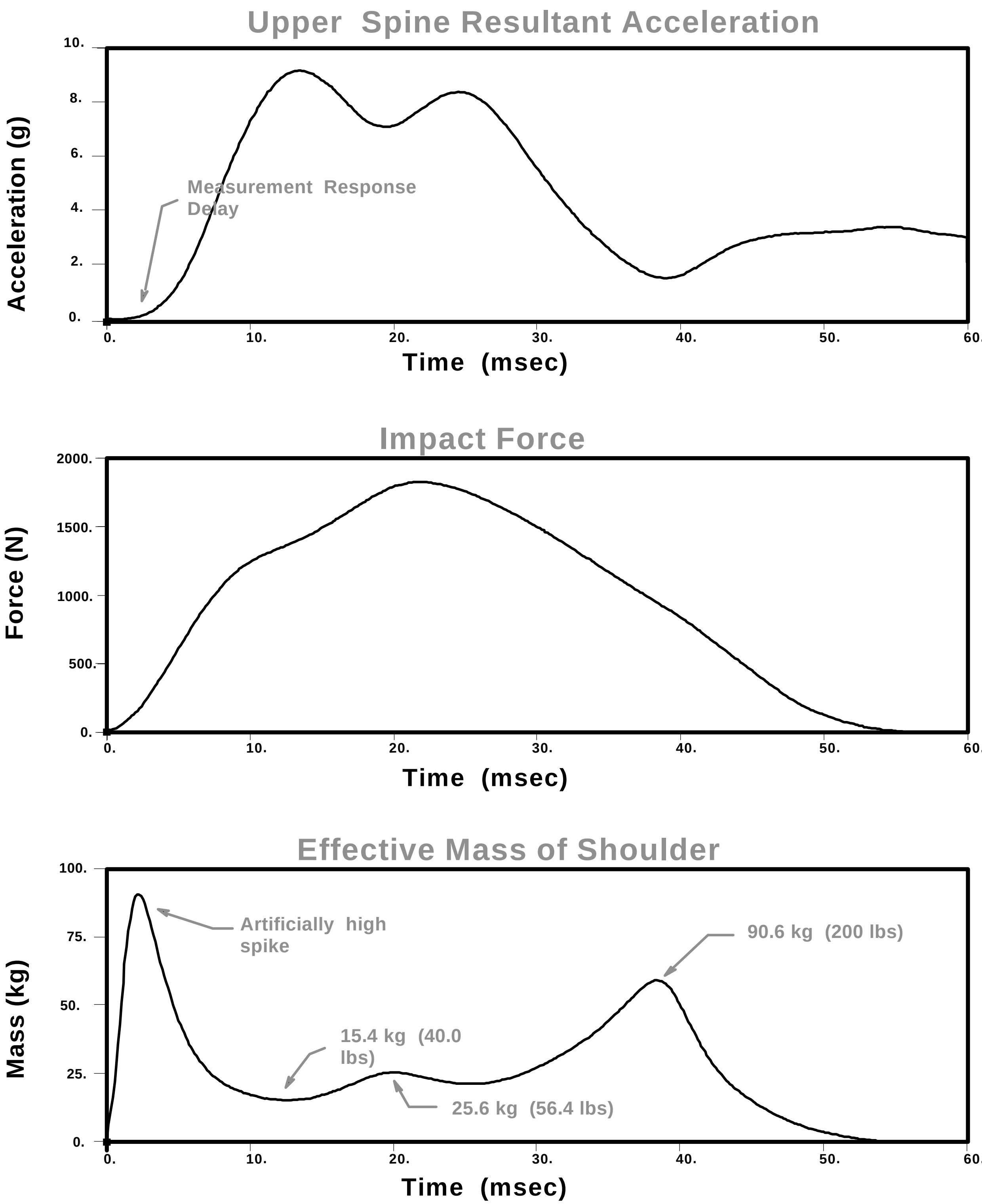


Figure 7.3 Shoulder Effective Mass from 2.7 m/s Pendulum Impact with Arcel Foam

more load plates were added in the 'glazing' area to measure shoulder and head impact forces. These plates were covered with the two stiffer paddings used in the pendulum tests, plus a softer padding. This softer padding, polystyrene, was chosen to be similar to DuPont's bilaminate glazing (based on the maximum deflection under certain impact conditions[5]). To simulate the curvature of a typical side window, the shoulder foam was offset from the door foam 51 mm (2 in) away from the dummy, and the head foam was offset from the door foam 51 mm toward the dummy.

Two impact conditions were chosen based largely on the results of the film and NASS analyses discussed previously. The first was the 'rollover' condition. In these tests, the BioSID was leaned toward the impact wall, such that the head and shoulder struck the 'glazing' at nearly the same time (see Figure 7.4). Although the film analysis showed that the heads actually struck the side roof rails, concurrent shoulder and head contact with the glazing certainly can occur. Since this represents the more severe case, this condition was simulated in the sled tests. These tests were conducted at 16.1 kmph (10 mph)..

The second condition was the 'side impact' condition. In these tests, the BioSid was seated upright, such that the head struck the 'glazing' prior to the shoulder (see Figure 7.5). These tests were run at 24 kmph (15 mph). Note that 24 kmph was selected rather than the 17.7 kmph (11 mph) suggested from the NASS analysis. There are a few reasons for this. First, the speeds reported from the NASS analysis were those found to cause side window disintegration, not necessarily those required to produce ejection. It is believed that ejection speeds would be higher on average. The upper interior head protection research indicated that a head to side structure speed of 24 kmph was typical of more serious crashes (those causing serious head injury). Also, from the NASS analysis, the most common delta-v was about 30.6 kmph (19 mph). For these reasons, and because a speed of 16.1 kmph (10 mph) was selected for the 'rollover' sled tests, the

[5] Peterson, B.S., Sursi, P.L., Glance, P., “Glass-Plastic Glazing for Side Window Ejection Reduction”, NHTSA Report DOT-HS-807-397, June 1989.

'side impact' test speed was chosen to be 24 kmph (15 mph). The matrix of sled tests is contained in Table 7.2

The total effective mass was calculated for each test. First, effective mass due to head contact was found using the force measured by the head load plate and the head c.g. resultant acceleration. The
effective mass due to the shoulder was found using the force measured by the shoulder load plate and

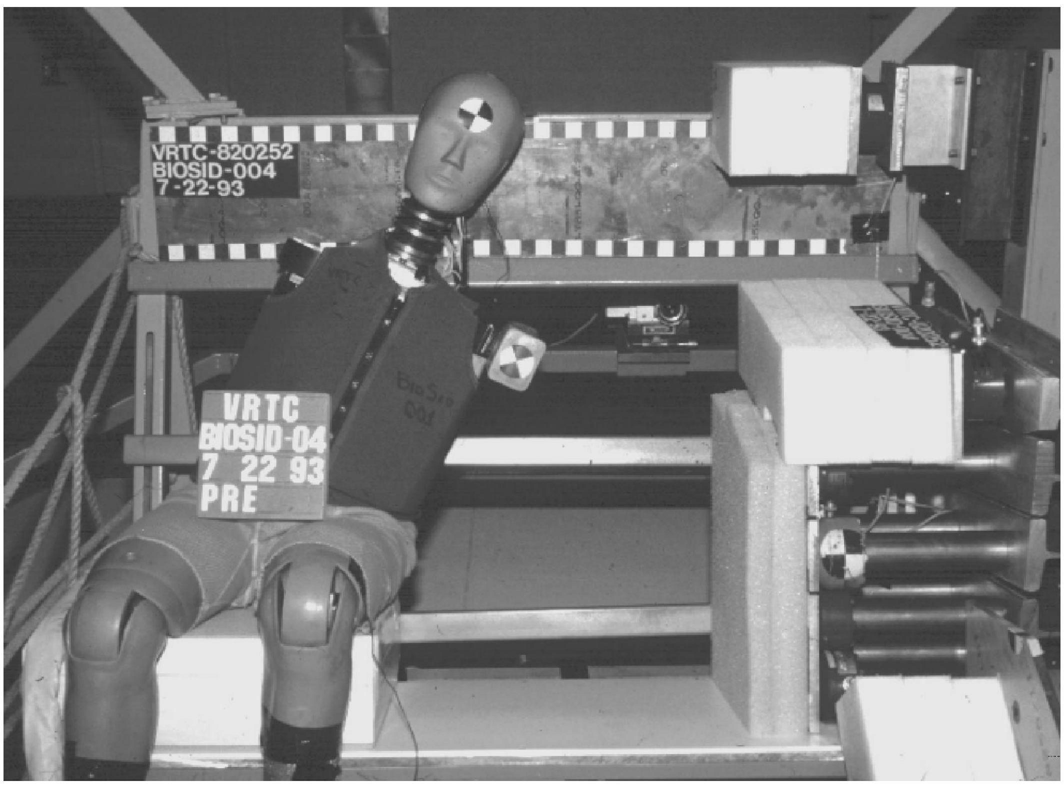


Figure 7.4 "Rollover" Sled Test Configuration

Table 7.2 Sled Test Matrix and Test Numbers

IMPACT MODE	IMPACT SPEED *kmph (mph)*	LOAD CELL WALL PADDING		
		Arsan	Ethafoam	Polystyrene
Side	24 (15)	TRC755	TRC754	TRC756
Rollover	16.1 (10)	TRC758	TRC757	TRC759

the T01 resultant acceleration. Since the head and shoulder contacts were part of the same event (unlike in the pendulum tests), their respective effective mass time histories were added to obtain the total effective mass seen by the 'glazing.'

The total effective mass time histories for the three side impact mode sled tests are shown in Figure 7.6. Note that the zero-divide phenomenon described previously also exists in these plots. For all three tests, the effective mass settles down at about 9 kg (20 lb), rising to about 18 kg (40 lb) over the next 20 msec or so.

The total effective mass time histories for the three rollover mode sled tests are shown in Figure 7.7. Due to the different loading condition on the dummy, there is not a lag in the T01 response, thus no zero-divide effect. In these traces, the effective mass quickly reaches 18 to 20 kg (40 to 45 lb), and then rises to about 41 to 43 kg (90 to 95 lb) over the next 20 msec or so.

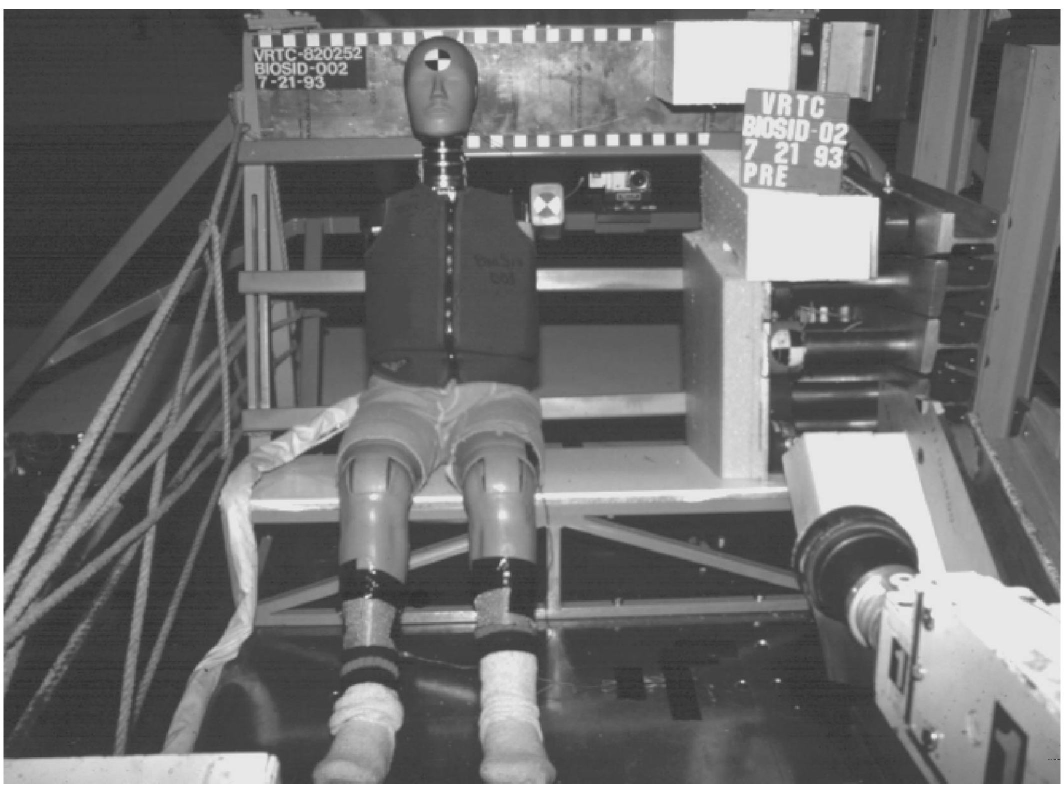
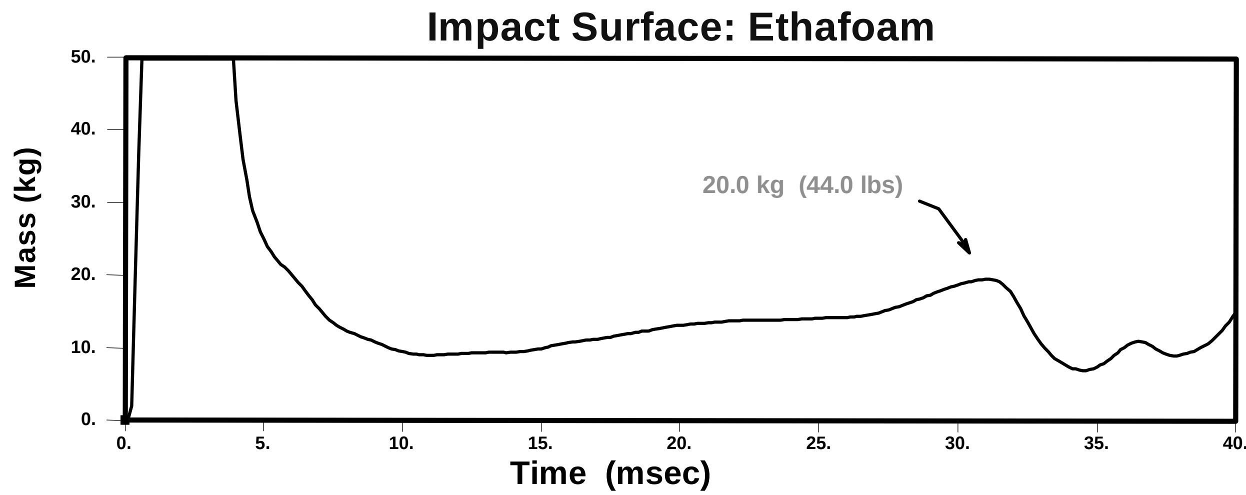
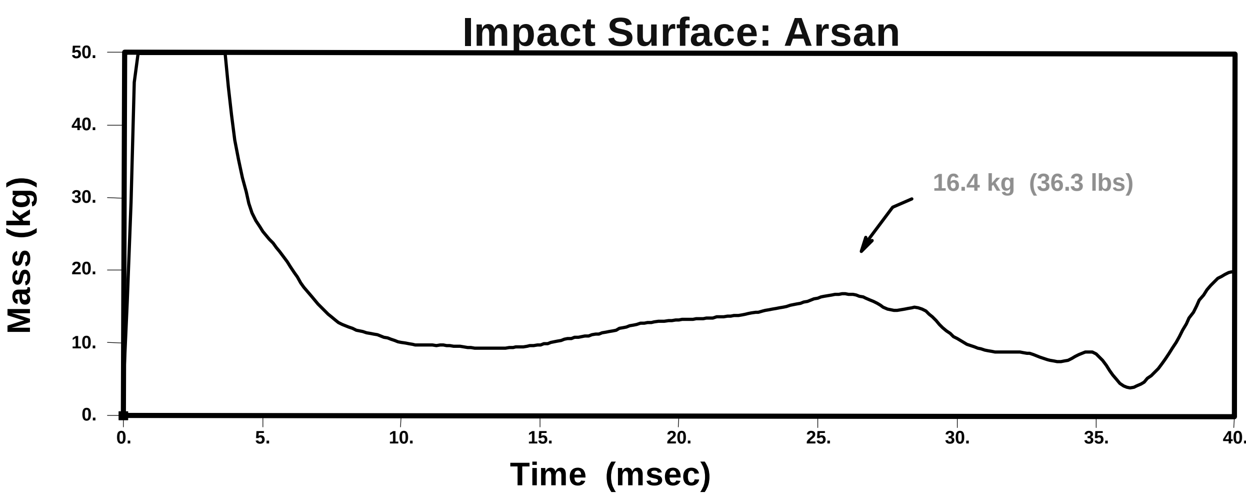
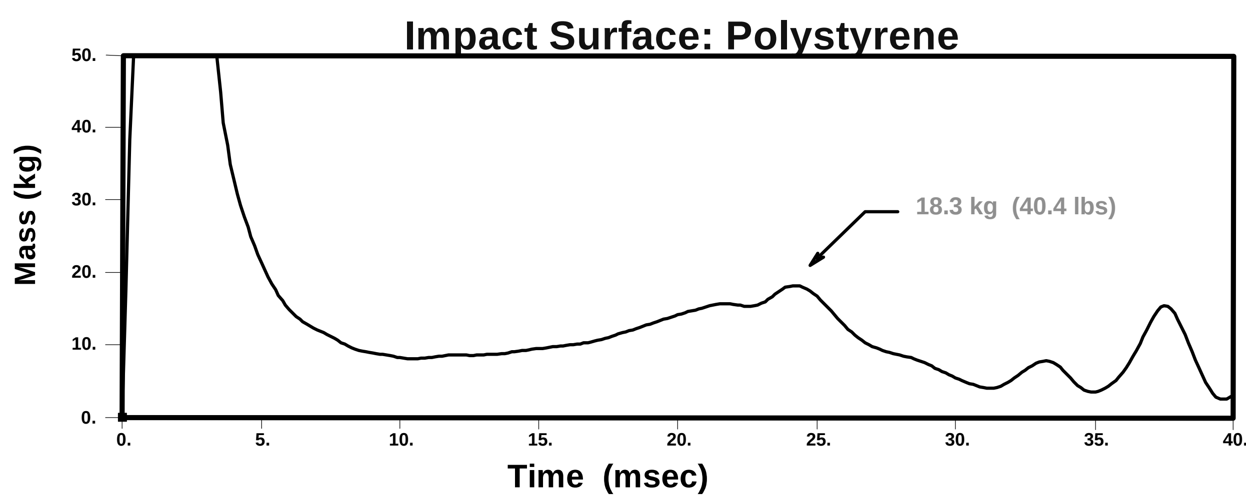


Figure 7.5 “Side Impact” Sled Test Configuration

These results tend to point to two different impact conditions: 9 kg at 24 kmph (20 lb at 15 mph) or 18 kg at 16.1 kmph (40 lb at 10 mph). In fact, these associated speeds are not completely accurate since the relative speed between the sled and the dummy begins to drop immediately following contact. Since the effective masses do not reach the values listed above for 5 to 10 msec, the true speeds are somewhat less than those stated here. Nevertheless, it was felt that these are reasonable estimates, good for the rollover mode, less good for the side impact mode.


Impact Surface: Ethafoam
Mass (kg)
50.
40.
30.
20.
10.
0.
20.0 kg (44.0 lbs)
0.
5.
10.
15.
20.
25.
30.
35.
40.
Time (msec)


Impact Surface: Arsan
Mass (kg)
50.
40.
30.
20.
10.
0.
16.4 kg (36.3 lbs)
0.
5.
10.
15.
20.
25.
30.
35.
40.
Time (msec)


Impact Surface: Polystyrene
Mass (kg)
50.
40.
30.
20.
10.
0.
18.3 kg (40.4 lbs)
0.
5.
10.
15.
20.
25.
30.
35.
40.
Time (msec)

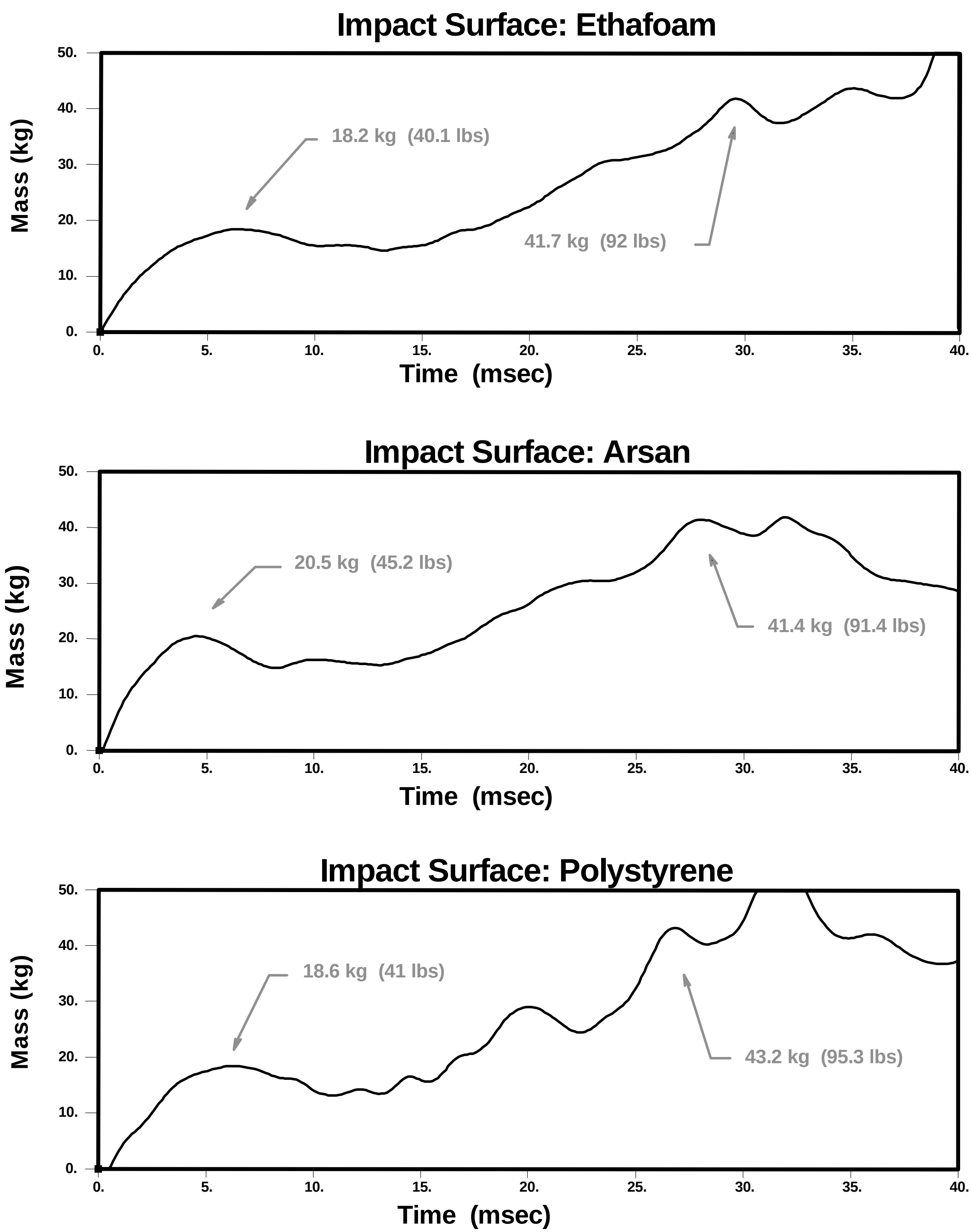


Figure 7.7 BioSID Effective Mass for “Rollover” Impact Test Configuration

A preliminary selection of 18 kg (40 lb) was made as the impacting mass. This was based on several considerations. First, the two sets of conditions stated in the previous paragraph represent similar levels of impact energy (180 to 200 N-m, 135 to 150 ft-lb). Some limited testing of windshields showed that for the same impact energy levels, the higher mass/slower speed test is more severe. Also, the results of the pendulum impact tests indicated that an effective mass in the range of 16 to 27 kg (35 to 60 lb) was an appropriate representation of the combined head/shoulder effective mass. Finally, occupant ejection through side glazings is, to a large extent, a rollover related problem. To recall, it was the 'rollover' sled condition that produced the 18 kg (40 lb) effective mass. Therefore, an impactor mass of 18 kg (40 lb) appears to be a reasonable selection at this phase of the research.

7.2.3 Finite Element Modelling

To verify the findings of the previous sled tests, the results were supplemented by finite element simulations comparing these sled tests with the impacts of an 18 kg impactor. A finite element (FE) model of the sled test was set up, which allowed calculation of the energy absorbed by the foam during the impact with the dummy.

An FE model of an 18 kg impactor impact into the foam covered wall was also set up (see Figure 7.8). The total energy absorbed by the foam and its loading history were compared between the two simulations. Since an FE model of Hybrid III dummy was readily available, it was used in the model instead of BioSID. Also, since in real situations the head and shoulder will impact the same glazing at two locations, one piece of foam was used for both head and shoulder contacts instead of two pieces of foam used in the sled test at shoulder and head level. A 152 mm (6 in) thick piece of foam was modeled with 4500 solid elements. The dummy's head, shoulder, and upper left arm were allowed to contact the foam. The dummy was modeled using rigid ellipsoids. As in the sled test, the dummy was leaned 26 degrees toward the foam and was given an initial velocity of 16.1 kmph (10 mph).

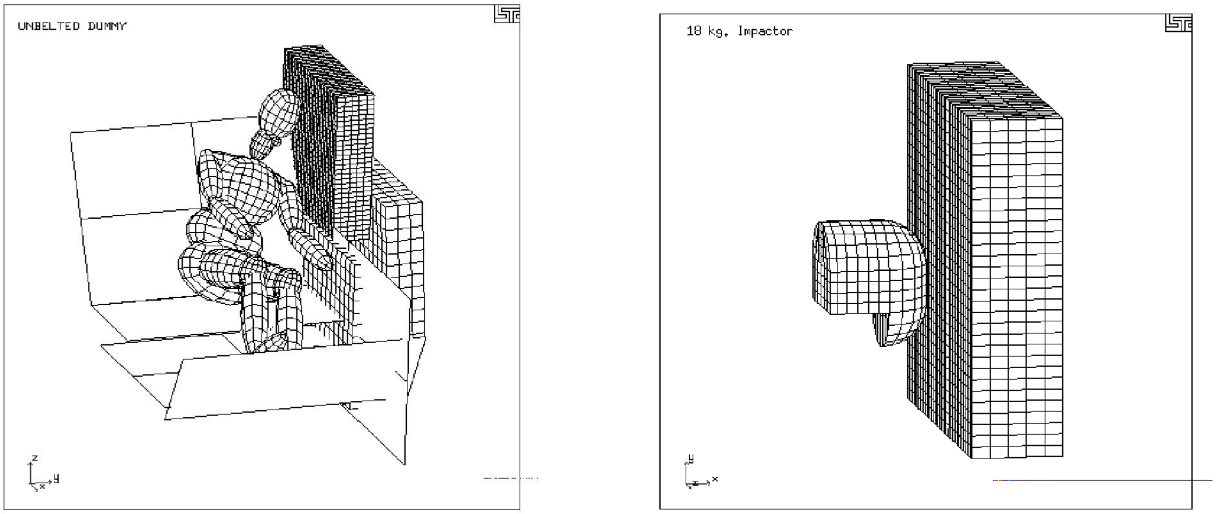


Figure 7.8 FE Models of Hybrid III and 18 kg Impactor Impacting Polystyrene Foam.

A number of simulations were run by changing the polystyrene foam properties to match the head accelerations in the model and the sled test. The results are plotted in Figure 7.9.   The model predicted a little longer contact duration and higher G's for the head as compared to the sled test.

Figure 7.9 Head Acceleration from Rollover Sled Test

Nevertheless, the results were assumed to be acceptable for a preliminary analysis of the loading pattern.

Using the same foam properties derived from the sled rollover model, an 18 kg impactor model was set up for a 16 kmph impact with the foam. The geometry of the impactor model was the same as the 18 kg featureless impactor used for impact testing (see section 7.4). The impactor was modeled with 750 solid elements. The material properties of a softer material were used to account for the skin cover (Young's modulus, somewhere between steel and aluminum). The energy transferred to the foam in the impactor simulation was compared with the energy transferred in the dummy impact simulation. The plots of energy comparison are shown in Figure 7.10.

Figure 7.10 Energy Comparison

The impact loading of the foam was computed by using energy balance between the impacting object (headform or dummy's head and shoulder) and the foam. The energy balance between the foam and impactor can be written as:

$$K.E._{i.o} = K.E._{f} + I.E._{f} + \text{Energy dissipated}$$

where $K.E_{i.o.}$ = Kinetic energy of impacting object

$K.E._{f}$ = Kinetic energy of foam

$I.E._{f}$ = Internal energy of foam

The polystyrene foam is highly compressible and has a very low Poisson's ratio. In the sled test, the foam was crushed due to the compression load from the dummy. The FEM simulation of the sled test also showed the failure of the foam model, once the load from the dummy reached beyond the maximum strength of the foam. The internal energy of the foam rose steeply once the elements in the model started to fail. For comparison, only the internal energy of the foam up to the point before the elements started to fail, was considered.

The energy comparison indicated that the loading patterns of the foam in the two cases were not the same. The 18 kg impactor transferred 179 Nm (132 ft·lb)of energy to the foam where as the dummy transferred 290 Nm (214 ft·lb) of energy to the foam. In the 18 kg impactor model, the kinetic energy of the impactor was transferred to the foam and then the impactor rebounded leaving significant crush energy in the foam. The energy plot from the headform impact showed a sharp rise and shorter duration. In the dummy impact, the head impacted the foam and bounced back, while the bulk of the impact energy was transferred to the foam through the shoulder and upper arm, which also carried the mass of the lower body. The dummy impact showed more gradual loading for a longer duration of time. The head left contact with the foam at about 30 msec, indicated by a vertical line in Figure 7.10. At that point, the internal energy of the foam was about 125 Nm (92 ft·lb). The shoulder carrying the mass of the lower body, continued to load the foam slowly until the internal energy of the foam reached 279 Nm (206 ft·lb). The elements in the foam started to fail once the internal energy reached 279 Nm.

Comparing the energy of the foam in the dummy impact at 30 msec and the maximum energy of the foam in the 18 kg impactor impact, it was found that the combined head and shoulder transferred 125 Nm of energy to the foam as compared to 179 Nm maximum energy transferred by the 18 kg (40 lb) impactor. The rest of the energy was transferred by the shoulder and arm, which continued to load the foam more slowly.

Hence, for a 16.1 kmph (10 mph) impact, one design criterion for the impactor is that the total energy transferred to the glazing should be at least 125 Nm (equivalent to 12.5 kg (26 lb) impactor). The upper limit for the impactor energy could be 279 Nm (equivalent to 27 kg (60 lb) impactor).

The comparison of the two impact models produced twe main findings. First, the loading patterns in the two cases are different. In the dummy impact, the load is transferred by the complex head neck joint, shoulder, and upper arm. Once the head bounced back, the shoulder and upper arm continued to load the foam. Second the total energy transferred by the 18 kg impactor is within the range of the total energy transferred by the entire dummy. For a 16.1 kmph dummy impact with the foam, the effective mass that came in contact with the foam is between 12.5 kg and 27 kg.

7.3 Impact Velocity Selection

Using many of the same arguments discussed above, an impact speed of 16.1 kmph would appear to be reasonable. Before deciding on that value, it was felt necessary to look into the practicability and appropriateness of requiring a side glazing to withstand of 16.1 kmph impact by an 18 kg impactor. First, current alternative side glazing concepts would appear to have no difficulty withstanding this level of impact. In previous NHTSA research[6], an 18 kg ball was dropped onto DuPont bilaminate glazings. The ball did not begin to penetrate these glazings until speeds of 32.2 kmph (20 mph) were reached. Clearly, at least this particular glazing could easily withstand an 18 kg impact at 16.1 kmph.

Although the DuPont product can withstand a very severe impact, the test conditions for side glazings should not necessarily be selected at that high a level. Remember that the potential for head and perhaps neck injury increases with increased glazing stiffness. Current High Penetration Resistant (HPR) windshields have been shown to be very effective in reducing occupant ejections, without increasing the risk of other occupant injuries[7]. Therefore, the strength of current windshields would appear to be a reasonable upper bound for side glazing strength.

In order to get a feel for windshield strength, an impactor unit was assembled that would propel an 18 kg (40 lb) guided impactor into a rigidly mounted windshield. The impactor face was taken from the General Motors developed guided impactor used early in the upper interior head protection research program[8]. It is hemi-spherical with a diameter of about 178 mm (7 in), and is covered with a skin of the same thickness and material as dummy headskin. Ford Tempo windshields were arbitrarily chosen and all impacts were to the center of the windshield.

A test run at 23.3 kmph (14.5 mph) completely penetrated the windshield, while a second test run at 23.2 kmph (14.4 mph) tore the inner plastic layer without completely penetrating it. Two other tests,

conducted at 21.7 and 22.2 kmph (13.5 and 13.8 mph) also tore the plastic inner layer, but did

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[6] Peterson, B.S., Sursi, P.L., Glance, P., "Glass-Plastic Glazing for Side Window Ejection Reduction", HNTSA Report DOT-HS-807-397, June 1989.

[7] Kahane, C. J., "An Evaluation of Windshield Glazing and Installation Methods for Passenger Cars", NHTSA Report DOT- HS-806-693, February 1985.

[8] Griswold, C. J., "Side Impact Component Test Development", Presented at the 9th International Technical Conference on Experimental Safety Vehicles, November 1982.

not completely penetrate the windshields. An 18 kg (40 lb) impact at about 22.5 kmph (14 mph) is apparently near the upper bound for the penetration resistance of this particular windshield. Since a very limited number of tests were conducted on just one type of windshield, this finding should be considered tentative. Also, an attempt to define an appropriate geometry for the impactor face, which likely affects a glazing's performance, was not made. Therefore, it is premature to choose a specific impact velocity at this time. A range of 16 and 24 kmph (10 to 15 mph) was recommended for subsequent testing.

7.4 Performance Criteria and Measurement

Four different potential performance criteria were considered as to whether they should be evaluated in the component test. These were retention capability, head injury potential, neck injury potential, and laceration potential. Obviously, this test must evaluate a glazing's ability to retain an occupant. It is felt that this test must also evaluate the head injury causing potential of alternative side glazings. It is not known at this time whether a measurement of laceration potential, is necessary. If it is, it may be best addressed in a test similar to the ANSI type tests currently required in Federal Motor Vehicle Safety Standard (FMVSS) No. 205.

At this time, it is also not known if alternative side glazings could significantly increase the potential for causing neck injuries. The upper neck loads recorded in the sled test series described previously were not of a level generally thought to produce serious neck injury. Also, as discussed in Chapter 6, finite element modeling suggests that the advanced glazings may not produce serious neck injuries. Further investigation of this is planned.

A component test impactor was designed to evaluate the occupant retention capability and head injury causing potential of alternative side glazings. It was decided that the retention capability would best be evaluated based on the dynamic deflection measurement of a guided impactor.

The impactor, shown in Figure 7.11, allows consistent testing conditions. It is instrumented to provide

displacement, acceleration and force, and its mass can be adjusted between testing. Since this impactor is guided, only uniaxial motion is measured. Impact velocity is measured by an optical sensor that records the time a beam of light is interrupted as a "flag", attached to the impactor, passes through it. The propulsion unit is based on a device developed by the General Motors Corporation[9], scaled up to accommodate the heavier mass. The impactor can be placed inside the vehicle for testing the side glazing/door system and can pivot up and down to allow testing at various angles.

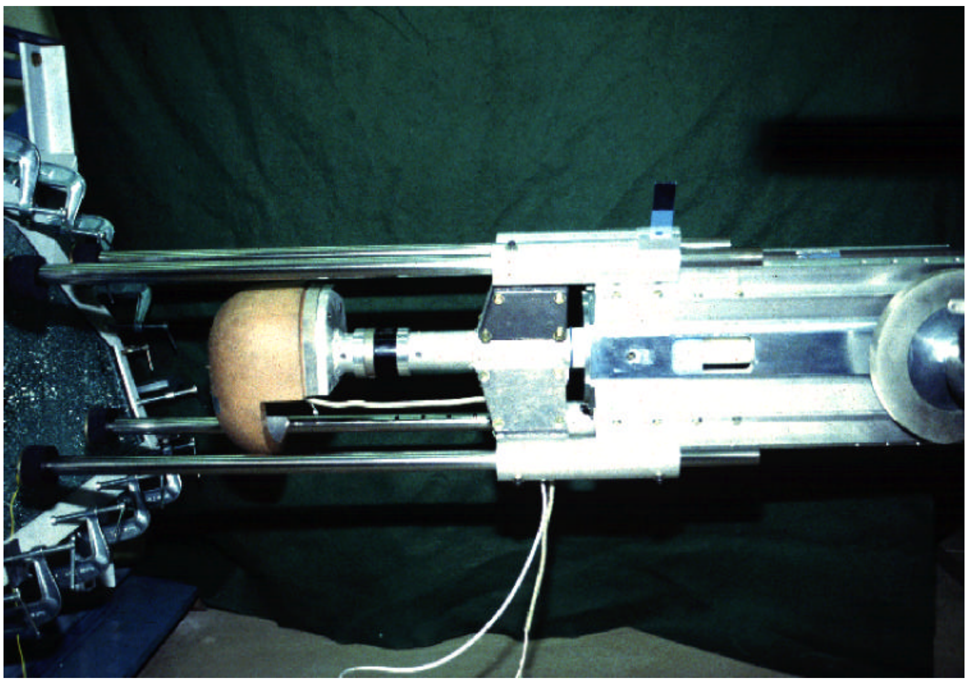


Figure 7.11 18 Kg. Guided Impactor

The harsh environment encountered in glass impact testing has been known to damage accelerometers, resulting in suspect data. The commonly used Endevco 7264-2000 model accelerometer was initially used in the 18 kg guided impactor tests. When this accelerometer was used in glass impacts which induced fracture, a number of unusual spikes often appeared in the

[9] Griswold, C.J., "Side Impact Component Test Development", Presented at the 9th International Technical Conference of Experimental Safety Vehicles, November 1982.

data. These spikes could not be explained by the expected reaction of the impactor. It is theorized that the high frequency event of glass fracture can excite the undamped natural resonate frequency of this accelerometer (rated at 25,000 hertz). An Endevco 7270A-2000 piezoresistive accelerometer, with a mounted resonate frequency of 95,000 hertz, was chosen for this program. Although not intended to provide data for direct performance measurement, the load cell data are valuable for validating the general shape of the acceleration time histories.

The impacting surface is the Featureless Free Motion Headform (FFMH), a rigid headform designed during the upper interior head protection research program that averages the dimensional and inertial

characteristics of the frontal and lateral regions of the head into a single headform[10]. The height of the headform measures 226 mm (8.9 in.) while the breadth measures 176.5 mm (6.95 in.). It was chosen because it was readily available and has a larger front "face" area than the Hybrid III headform, thereby better approximating the loading condition of the head and shoulder contacting the side glazing simultaneously. A brief examination of the geometry influence on the advanced glazings' performance was conducted, as described in the next section.

7.5 Advanced Side Glazing Impact Testing

The performance measurements of particular concern in the glazing tests include the impactor displacement to measure the dynamic deflection of the glazing system, and the acceleration pulse for the HIC calculations. Prior to testing, it was recognized that because the impactor is constrained to uniaxial motion, it cannot reproduce the trajectory or accelerations and forces that would be experienced by the Hybrid III head during full dummy testing. Furthermore, the HIC-1000 criterion for head injury is meaningless when directly applied to the acceleration measurement from an 18 kg (40 lb) impactor. While future research may include developing a transform to account for these factors, the HIC values listed in this chapter are only to be used

[10] Howe, J.G., Willke, D.T., Collins, J.A., "Development of a Featureless Free-Motion Headform", SAE Paper Number 91209, November 1991.

to compare the relative performance of the various glazings and should not be evaluated using the HIC-1000 criterion.

7.5.1 Rigidly Clamped Testing

The first part of the testing program focused on determining if the advanced glazings under study could absorb and contain the impacts of the proposed energy levels. Impact tests were conducted on nonencapsulated glazings with fully constrained edges so that material failure would occur before any edge failure was seen. The stiffness of the frame, shown in Figure 7.12, ensured that essentially no frame deflection occurred during the impact event.

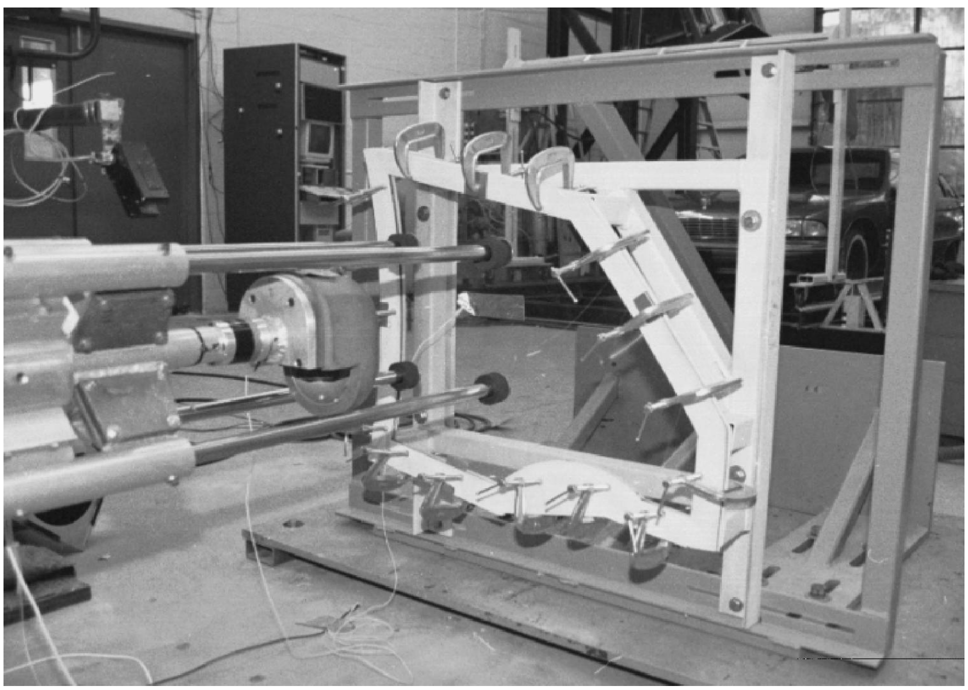


Figure 7.12 Rigidly Clamped Impact Test Hardware

The impactor was positioned such that the impact location was at the glazings geometric center. For each test, displacement, acceleration and force measurements were recorded. The displacement was measured as the amount of impactor travel once contact was made. The accelerations were filtered with an SAE Class 1000 analog filter prior to digitization and HIC values were then calculated. Damage to the glazing material was noted including the extent of headform penetration into the glazing. High speed film captured the event for further analysis.

Figure 7.13 shows the acceleration time histories from selected tests. The acquired data were sampled at 12.5 kHz. The resulting responses contained anomalous spikes and conflicting data that cannot be explained by the expected reaction of the impactor. The suspect data appeared after the inertial loading of the glazing, that is, after the initial glass fracture and before plastic deformation. At this point it appears that the glass impacts are releasing considerable energy at high frequencies and affecting the undamped accelerometer's natural resonate frequency. This can lead to driving the accelerometer into a non-linear region. Furthermore, in many tests the HIC calculation was maximized over this portion of the curve, resulting in extremely large and erroneous HIC values.

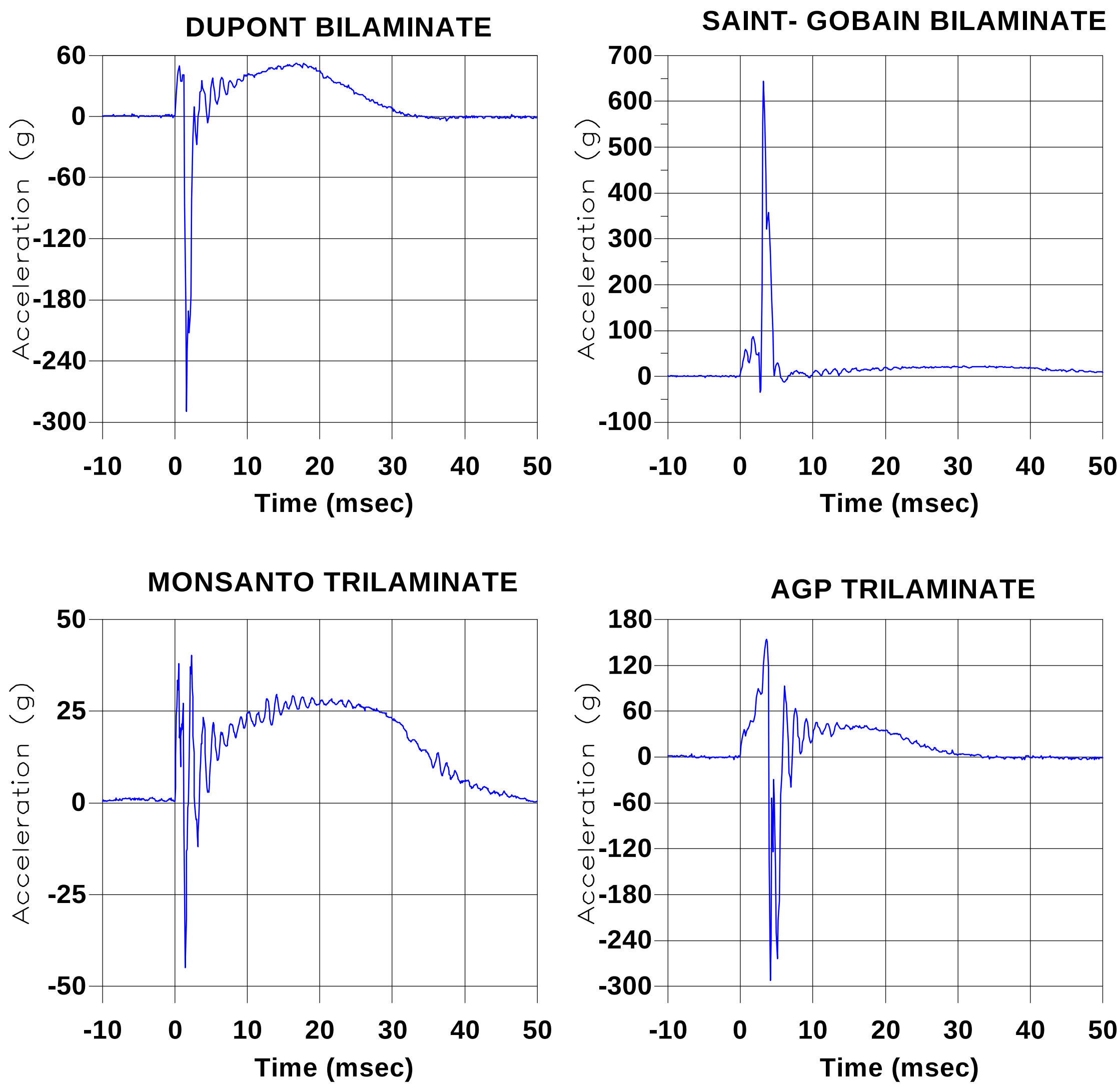


Figure 7.13 Acceleration Time Histories from Selected Impact Tests Showing Anomalous Spikes in Data

An investigation into this phenomena is presently being conducted by the Advanced Glazing Research Team. Several different types of accelerometers are being used in the testing to evaluate their characteristic responses during glass impact tests. This includes the evaluation of an internally damped accelerometer unit and undamped units with resonate frequency ratings above 100,000 Hz. In addition, changes to the mechanical mounting configuration were made.

No significant changes have been observed in the responses. It is therefore believed that the dynamic characteristics of the test device itself may be contributing to the accelerometer output. The impactor may not behave as a rigid body and may be exhibiting low natural frequencies which are contaminating the data. Effort is being put forth to quantify the impactor's dynamic characteristics so that a suitable design modification can eliminate or raise these natural frequencies.

The results of the rigidly clamped tests are summarized in Table 7.3. Although HIC calculations are not part of the evaluation, an initial assessment of the glazings containment capability can be made with the 18 kg (40 lb) impactor. It is recognized that the energy containment assessment may be conservative in the rigidly clamped tests since additional energy absorption through window frame distortions are not included.

The results show that the DuPont and Saint-Gobain bilaminates and AGP's trilaminate are capable of containing the target energy under the specified restraint conditions. It appears that this energy level is near the upper boundary limit for the Monsanto trilaminate. This appears to be the case for impacts using the 178 mm hemi-spherical headform. However, the thickness of the PVB interlayer can be increased for additional penetration resistance. The performance of this particular construction has highlighted a performance issue that may need further attention. Figure 7.14 shows the result of full headform penetration. The fracture characteristics of the annealed glass produces long, slender shards that may produce serious lacerations. The laceration potential of this particular construction should be addressed in future research.

Observations from high speed films shows that when the tempered glass is broken by the impact, most of the glass particles remain attached to the bilaminate layer. Impacts to the annealed glass (trilaminate) however, send glass particles scattering through the air.

Table 7.3 Rigidly Clamped Impact Test Results

TEST #	CONFIGURATION	TEST VELOCITY *kmph (mph)*	IMPACTOR MASS *kg (lb.)*	IMPACTOR HEADFORM	MAXIMUM DEFLECTION *mm (in.)*	PENETRATION EXTENT
DU01	DuPont Bilaminate	24.3 (15.1)	18 (40)	FFMH	84.4 (3.3)	No Tearing of Plastic Interlayer
DU02	DuPont Bilaminate	15.9 (9.87)	18 (40)	FFMH	55.3 (2.2)	No Tearing of Plastic Interlayer
DU03	DuPont Bilaminate	24.5 (15.2)	18 (40)	FFMH	86.8 (3.4)	No Tearing of Plastic Interlayer
DU04	DuPont Bilaminate	24.1 (15.0)	18 (40)	FFMH	80.9 (3.2)	No Tearing of Plastic Interlayer
SG01	Saint-Gobain Bilaminate**	24.8 (15.4)	18 (40)	FFMH	182 (7.2)	No Tearing of Plastic Interlayer
SG03	Saint-Gobain Bilaminate	24.3 (15.1)	18 (40)	Hemispherical Headform	190 (7.5)	No Tearing of Plastic Interlayer
SG04	Saint-Gobain Bilaminate	24.1 (15.0)	18 (40)	Hemispherical Headform	162 (6.4)	No Tearing of Plastic Interlayer
SG05	Saint-Gobain Bilaminate	24.1 (15.0)	18 (40)	FFMH	149 (5.9)	No Tearing of Plastic Interlayer
SG06	Saint-Gobain Bilaminate	24.1 (15.0)	18 (40)	Hemispherical Headform	174 (6.8)	No Tearing of Plastic Interlayer
SG07	Saint-Gobain Bilaminate	16.6 (10.3)	18 (40)	FFMH	106 (4.2)	No Tearing of Plastic Interlayer
SG08	Saint-Gobain Bilaminate	24.8 (15.4)	18 (40)	FFMH	142 (5.6)	No Tearing of Plastic Interlayer
SG09	Saint-Gobain Bilaminate	24.0 (14.9)	18 (40)	FFMH	152 (6.0)	No Tearing of Plastic Interlayer
SG10	Saint-Gobain Bilaminate	24.3 (15.1)	18 (40)	FFMH	151 (5.9)	No Tearing of Plastic Interlayer
SG11	Saint-Gobain Bilaminate	24.1 (15.0)	18 (40)	FFMH	150 (5.9)	No Tearing of Plastic Interlayer
MO02	Monsanto Trilaminate	24.8 (15.4)	18 (40)	FFMH	125 (4.9)	No Tearing of Plastic Interlayer
MO03	Monsanto Trilaminate	24.8 (15.4)	18 (40)	FFMH	194 (7.6)	Interlayer Torn; Nearly Complete Penetration
MO04	Monsanto Trilaminate	24.6 (15.3)	18 (40)	FFMH	143 (5.6)	Interlayer Torn but no Penetration
MO05	Monsanto Trilaminate	24.5 (15.2)	18 (40)	FFMH	185 (7.3)	Headform Completely Penetrated
MO07	Monsanto Trilaminate	24.3 (15.1)	18 (40)	Hemispherical Headform	181 (7.1)	Headform Completely Penetrated
MO08	Monsanto Trilaminate	15.3 (9.5)	18 (40)	FFMH	73 (2.9)	No Tearing of Plastic Interlayer
MO09	Monsanto Trilaminate	24.0 (14.9)	18 (40)	FFMH	123 (4.8)	No Tearing of Plastic Interlayer
MO10	Monsanto Trilaminate	24.1 (15.0)	18 (40)	FFMH	149 (5.9)	Interlayer Torn but no Penetration
AG02	AGP Trilaminate	24.6 (15.3)	18 (40)	FFMH	70 (2.7)	No Tearing of Plastic Interlayer
AG04	AGP Trilaminate	24.9 (15.5)	18 (40)	FFMH	59 (2.3)	No Tearing of Plastic Interlayer
AG06	AGP Trilaminate	24.3 (15.1)	18 (40)	Hemispherical Headform	78 (3.1)	No Tearing of Plastic Interlayer
AG07	AGP Trilaminate	24.3 (15.1)	18 (40)	FFMH	59 (2.3)	No Tearing of Plastic Interlayer
AG08	AGP Trilaminate	24.1 (15.0)	18 (40)	FFMH	67 (2.7)	No Tearing of Plastic Interlayer
AG09	AGP Trilaminate	23.8 (14.8)	18 (40)	FFMH	55 (2.2)	No Tearing of Plastic Interlayer

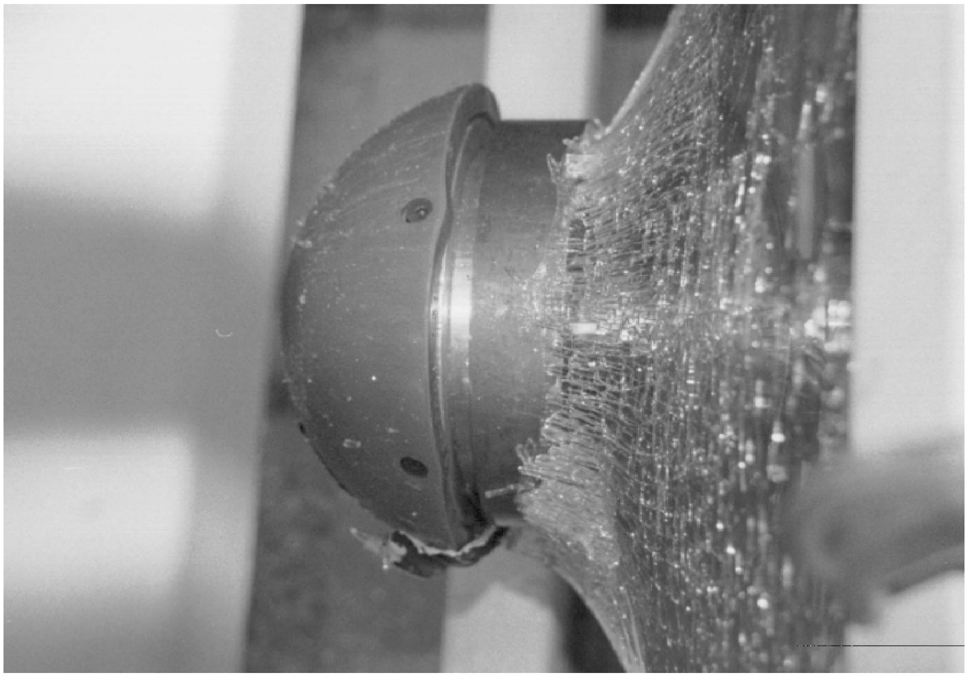


Figure 7.14 Hemispherical Headform Penetration Showing Laceration Potential of Annealed Glass Particles

7.5.2 Modular Glazing System Testing

This part of the program involves a joint effort by the respective glazing suppliers, Excel Industries and VRTC to develop a side glazing module capable of containing impacts of the proposed energy levels. Tests using the 18 kg impactor were conducted on the LTD door/advanced glazing system (see Chapter 4) to determine if the modified L-edge is capable of retaining the glazing material in the window frame without failure of the bond at the interface or failure of the window frame modifications. The test setup is shown in Figure 7.15. The door was attached to the rigid frame used in previous testing, in an orientation similar to its position on the LTD vehicle. The impactor was angled 23° upwards to maximize the surface area that first contacts the glazing (future tests will be conducted with the impactor parallel to the ground to assess the impact angle's influence on performance).

The featureless impactor face was instrumented with various accelerometers and a linear potentiometer recorded the impactor displacement and ultimately, the dynamic deflection of the modular glazing system. The window frame was instrumented at two locations near the top edge to measure frame deflection. The window was fully closed and the impact was centered on the geometric center of the glazing area.

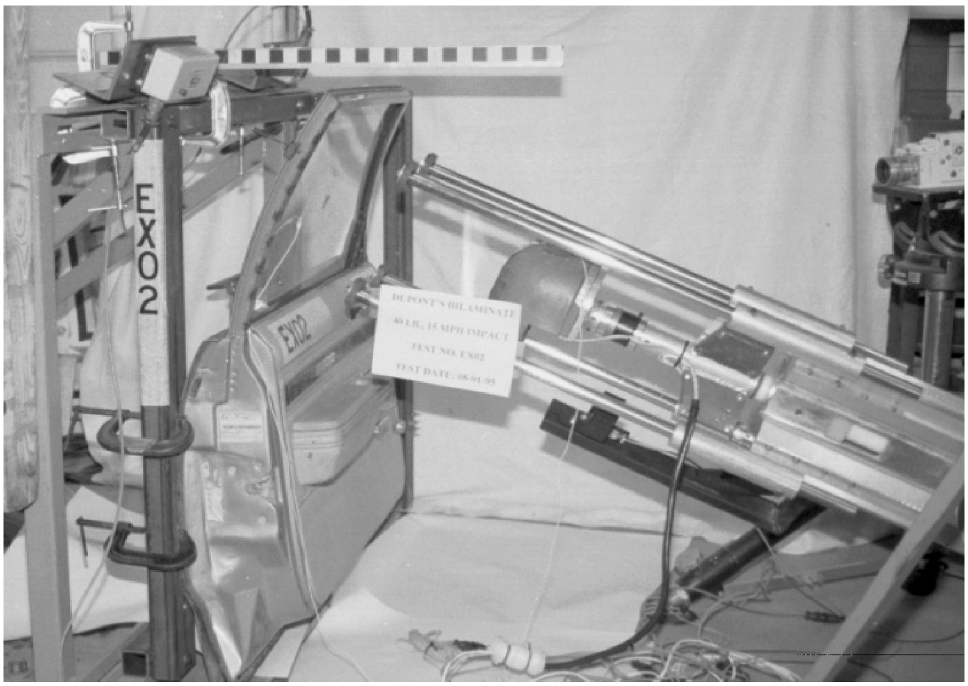


Figure 7.15 Modular Glazing System Test Setup

The test results showed that adequate retention was maintained in the area of encapsulation but that the unsupported (nonencapsulated) top edge was subject to large deflections during the impact. This was followed by recovery of the glazing material. These large dynamic deflections are illustrated for three of the advanced glazing systems in Figure 7.16 which shows the maximum point of deflection, captured from high speed films. Based on the dynamic deflection measurement of the impactor, the DuPont bilaminate performed the best with a 144 mm (5.7 in) deflection measurement. The impactor displaced 172 mm (6.8 in) when impacted into the Monsanto trilaminate and 217 mm (8.5 in) for the Saint-Gobain bilaminate. Note that in Figure

7.16, however, the gap created between the glazing and door frame was the smallest for the Monsanto trilaminate. In all tests the impactor was brought to rest by the modular glazing system well before reaching the physical 'stops' on the impactor's guidance system. Test conclusions are considered tentative at this time until more testing has been completed.

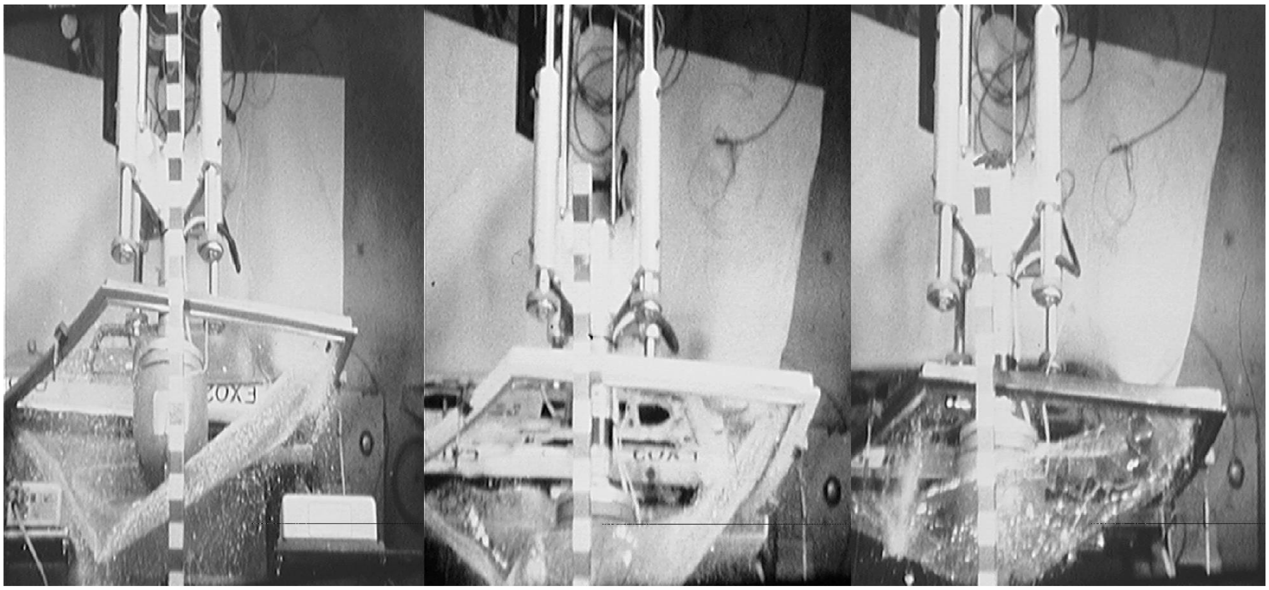


Figure 7.16 Point of Maximum Dynamic Deflection for DuPont (left), Saint-Gobain (center) and Monsanto Advanced Glazings

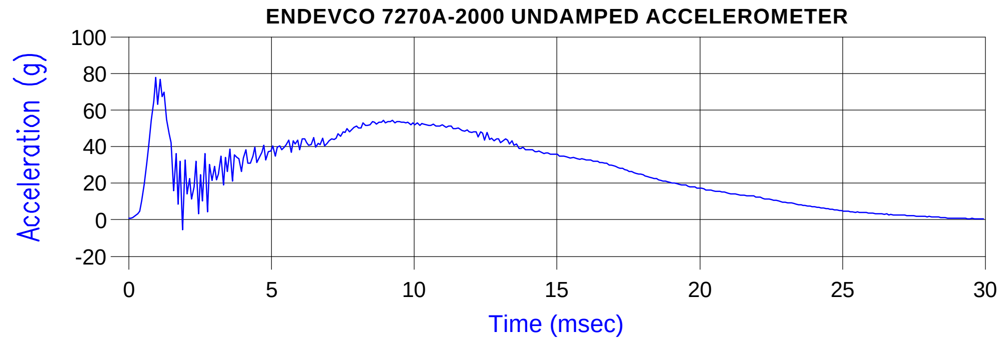
7.5.3 Free-Motion Headform Testing

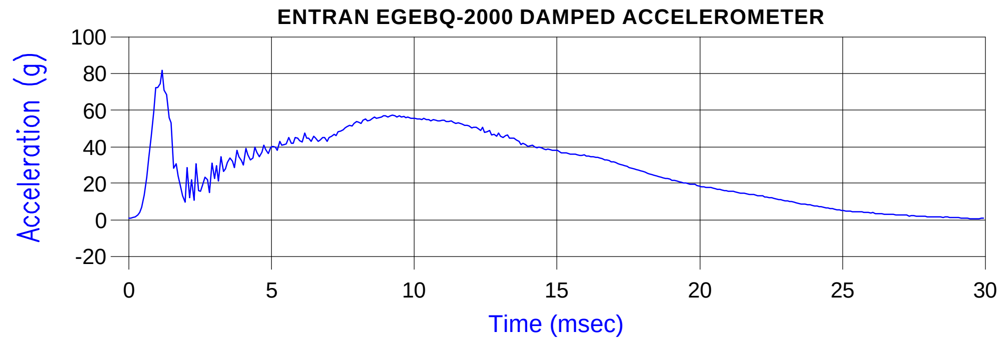
In order to explore the assumption that the dynamic characteristics of the guided impactor are partially responsible for the unusual pulse shapes, a short series of free-motion headform impacts was conducted into both laminated (windshield) and tempered glass using accelerometers of different design. The glazing impact tests were conducted on vehicles so that no special mounting system was required. The tests were intended to be a quick assessment of the effect of the glazing environment on a free-motion type impactor and not a rigorous examination of any particular glass type or mode of impact. The free-motion headform (FMH) established for use in the recent upgrade of FMVSS 201 was used[11]. The FMH is a Hybrid III head, weighing, 4.5 kg (10 lbs.), modified for use in a free-motion impactor. It was instrumented with three accelerometers acting along the longitudinal axis of the headform and positioned as close to the center of gravity as possible. The three accelerometers included Endevco's 7264-2000 and 7270-2000 models and Entran's EGEBQ-2000 damped unit. Data were collected in the manner described above.

Figure 7.17 shows the acceleration time histories from a 24 kmph impact into a windshield. As can be seen, the Endevco 7270A-2000 and Entran units display reasonable responses while the 7264-2000 unit still contains an anomalous spike in the inertial loading part of the curve. Similar results occurred in all tests including tempered glass. To further pinpoint the problem, the FMH was replaced by the FFMH and tested under the same conditions. The 7264 unit was not used in these tests. The results from these were tests were encouraging as well.

The results from the entire test series are summarized in Table 7.4. It is interesting to note that impacts to tempered side glass which did not result in fracture, produced higher HIC values than tests conducted on the same glass piece, tested at higher speeds to ensure glass fracture. It should be pointed out that the HIC values were calculated from only one component (longitudinal direction) of the resultant acceleration pulse. Space limitations inside the headform prevented a tri-axial configuration for the different accelerometers. Because free-motion testing produces headform rotation, there is usually significant accelerations in the other components which would add to the
overall HIC calculation.

[11] FMVSS No. 201 Final Rule; Volume 60, Number 160; Docket Number 92-28, Notice 4; August, 1995.


ENDEVCO 7270A-2000 UNDAMPED ACCELEROMETER
Acceleration (g)
100
80
60
40
20
0
-20
0
5
10
15
20
25
30
Time (msec)


ENTRAN EGEBQ-2000 DAMPED ACCELEROMETER
Acceleration (g)
100
80
60
40
20
0
-20
0
5
10
15
20
25
30
Time (msec)

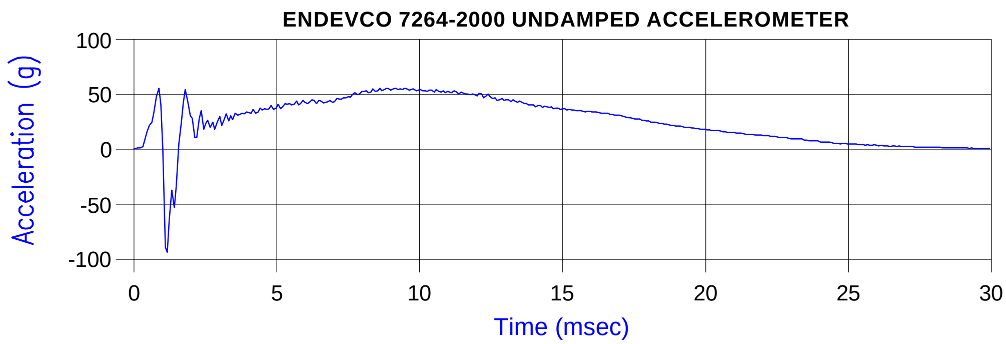

ENDEVCO 7264-2000 UNDAMPED ACCELEROMETER
Acceleration (g)
100
50
0
-50
-100
0
5
10
15
20
25
30
Time (msec)

Table 7.4 FMH/Glazing Impact Test Results

TEST #	HEADFORM TYPE	IMPACT SPEED	IMPACTING SURFACE	HIC VALUES			COMMENTS
				ramxg[1]	*ramxga*[2]	*ramxgc*[3]	
FMH1	FMH	24 kmph	Tempered Glass	NA	63	1083	Glass shattered upon impact
FMH2	FMH	24 kmph	Windshield	170	195	184	
FMH3	FMH	24 kmph	Tempered Glass	404	463	430	Glass did not break
FMH4	FMH	32 mph	Tempered Glass	59	57	39014	Glass shattered upon impact
FMH5	FFMH*	24 kmph	Windshield	123	139	NA	
FMH6	FFMH	24 kmph	Tempered Glass	402	460	NA	Glass did not break
FMH7	FFMH	28 kmph	Tempered Glass	230	252	NA	Glass shattered upon impact

* Featureless Free Motion Headform (used on Glazing Impactor)

[1] Endevco 7270A-2000 Accelerometer (90, 0000 Hz Resonant Frequency)

[2] Entran EGEBQ-2000 Damped Accelerometer

[3] Endevco 7264-2000 Accelerometer (25,000 Hz Resonant Frequency)

Due to the encouraging results from this limited test program, the Advanced Glazing Team has decided to incorporate the FMH Test as part of the component test development. Although this decision adds complexity and effort to the research, it is a reasonable decision, as initiating the effort to eliminate the problem in the 18 kg impactor at this time will only further delay the program's advancement.

Initial testing has begun using the FMH test on the advanced glazing module system. For this testing, the FMH was instrumented with Endevco's 7270A-2000 unit in a tri-axial configuration. The headform was aligned with the test fixture to impact the window at its geometric center. For all impact tests, the headform was angled 5° downward. This was done to ensure that initial contact occured in the FMH forehead impact zone, as prescribed in the upgrade to FMVSS 201. The results from the initial test round are summarized in Table 7.5.

Table 7.5 FMH/Advanced Glazing Test Results

TEST #	IMPACT SPEED	IMPACTING SURFACE	HIC	COMMENTS
0252FM01	15.8 mph	Saint-Gobain Bilaminate	106	Top and right diagonal corner pulled out of window frame
0252FM02	15.3 mph	Monsanto Trilaminate	570	Glass did not break and remained in window frame
0252FM03	18.0 mph	Monsanto Trilaminate	858	Glass broke and remained in window frame
0252FM04	15.4 mph	Dupont's Bilaminate	137	Top and right diagonal corner pulled out of window frame
0252FM05	15.2 mph	Makrolon Polycarbonate	256	Glazing remained in window frame
0252FM06	18.0 mph	Makrolon Polycarbonate	426	Glazing remained in window frame
0252FM07	18.4 mph	Lexan Polycarbonate	180	Lexan cracked completely thru in lower corner of A-pillar verticle edge
0252FM08	15 mph	Tempered Glass	27	Glass shattered upon impact
0252FM09	12.4 mph	Tempered Glass	37	Glass shattered upon impact

8 COST, WEIGHT AND LEADTIME ANALYSIS

8.1 Introduction And Background

To determine the effects to automobile consumers and automobile manufacturers if side windows were equipped with glazing other than tempered glass, a cost, weight and leadtime analysis was conducted. The study determined the incremental costs to manufacturers if an alternative glazing was used to make side windows of automobiles, the incremental weight of the vehicle and a projected leadtime needed to produce enough glazing to accommodate the automobile industry.

The agency contracted with Management Engineering Associates (MEA) to perform a cost, weight and leadtime study of the use of a trilaminate, a bilaminate and a rigid plastic in the side window of automobiles. The contractor was given the responsibility of estimating variable manufacturing costs of producing each type of alternative glazing and tempered glass and the capital equipment and tooling cost associated with production of each type of glazing. Also MEA estimated installation costs. In addition, the contractor identified any vehicle modifications necessary to accept the alternative glazing specified. With this information wholesale and retail cost for each type of glazing were derived. The incremental costs were then derived by subtracting the derived cost for tempered glass from the derived cost for each alternative glazing analyzed.

8.2 Study Parameters

Limited time and funding for this project constrained the cost, weight and leadtime study to one high volume vehicle, the 1995 Ford Taurus. Therefore, the estimates derived and presented in this chapter are specifically for a 1995 Ford Taurus. Industry costs can not be derived without further study of various vehicles side window and door designs. However, the estimates contained in this chapter provide a valuable initial indication as to the cost and weight changes that will occur if one of the specified alternative glazings is used in side windows.

MEA conducted cost, weight and leadtime analysis on the following materials for use in side windows:

Tempered Glass - Glazing produced by cutting, bending, and tempering annealed flat glass. Tempered glass is used frequently in side windows of automobiles and is the base design of this study.

Trilaminate - Glazing produced by laminating a polyvinyl butyryl (PVB) film between two sheets of annealed glass. This study estimated the cost of the PVB produced by the Monsanto Corporation and the laminating processes of AP Technoglass.

Bilaminate - Two bilaminate designs were evaluated in this study. One was DuPont "Sentry-Glas" which is produced by laminating a film produced by DuPont composed of layers of PVB and Polyester (MYLAR), plus an abrasion resistant silicone coating onto a single sheet of tempered glass. The other design was by St. Gobain Vitrage, headquartered near Paris, France. St. Gobain uses a proprietary process in which two formulations of polyurethane are laminated on tempered glass. The urethane layer next to the glass is formulated to have high impact resistance. The external polurethane layer is made from a harder formulation to withstand abrasion.

Rigid Plastic - Windows are injection molded using polycarbonate resins.

Encapsulation - Initial research showed a need to strengthen the window to hold passengers in the automobiles. This study evaluated the process of encapsulating the windows on the front and back edges as a means of keeping the alternative glazing windows in the vehicle door opening. Cost estimates are provided for an encapsulation process which uses urethane components. Two part urethane components react when introduced to a mold and harden on the glazing panel that has been primed. To avoid degradation when exposed to sunlight a masking material is painted in the mold cavity.

Abrasion Resistant Coating - Rigid Plastics are prone to abrasion/scratching in the as-molded state. Therefore, the cost of applying an abrasion resistant coating to the rigid plastic analyzed was estimated. This study estimated the cost of using compounds of silicon (polysiloxenes) for the abrasion resistant coating. The rigid plastic will have to have a prime applied by either dipping it into the prime or spraying the prime onto the rigid plastic before the abrasion resistant coating is applied.

8.3 Research Protocol

Management Engineering Associates identified the industry components relevant to this research and conducted literature searches regarding current technologies in encapsulation and abrasion resistant coatings. Additionally, teleconferences were held with authorities in flat glass, automotive glazing fabrication, polymer molding, plastics coating, encapsulation, and automobile assembly industries to learn essential processes, technical considerations, costs, and capacity limitations. In order to insure that information reported was accurate and representative, multiple information sources were used and the results cross-correlated. Inconsistencies were eliminated. William Ward, President of MEA visited operations of AP Technoglass at Elizabethtown, KY and Excel Industries, Laurenceburg, TN to improve his knowledge of recent technology and industry constraints. He also visited major glass plants operated by Guardian Industries and United Glass. The information obtained during these visits, the teleconferences and literature searches allowed MEA to establish composite process and cost data.

8.4 Summary Of Findings

Table 8-1 summaries the cost results of manufacturing, encapsulating, installing and where appropriate the cost of applying abrasion resistant coating of each glazing alternative for one 1995 Ford Taurus front window. The chart also gives the weight of one window, incremental capital equipment estimates and leadtime estimates for each glazing material analyzed. From this information the wholesale and retail prices and the incremental cost to consumers as shown in Table 8-2 was estimated.

The information presented in Table 8-2 was derived from analysis of suppliers and vehicle manufacturers financial data. It shows that the wholesale price and suggested retail price of the alternative glazings are four to six times higher than the estimated wholesale price and suggested retail price of $28.56 and $32.04 for tempered glass. The incremental cost to the consumer (the price the consumer will incur for the use of alternative glazing versus tempered glass) is between $96.00 and $158.76 depending on the glazing design used. These costs will vary by car design. Additional study is needed of various vehicle designs before an industry wide estimate can be established.

8.5 Weight Estimates

Table 8-1 shows that the rigid plastic glazing will offer the most advantages in the reduction of weight. It is half the weight of existing tempered glass and will offer a reduction of approximately 18 pounds to the vehicle if used instead of tempered glass. The trilaminate, DuPont "Sentry-Glas" and St. Gobian Bilaminate weigh approximately the same as each other and tempered glass. These alternatives will provide an insignificant reduction of weight to the total vehicle.

8.6 Capital Equipment And Tooling Investment Estimates

All the alternatives analyzed are unique to use in automobile side glazing. Therefore, if the agency standardized the use of one of the four alternatives analyzed in this study it would necessitate the creation of a new industry. This would mean a huge outlet of capital. Since DuPont "Sentry-Glas" and St. Gobain Bilaminate are tempered glass with one layer of laminated film over the glass, existing plants and equipment used to manufacturer tempered glass can be used in their production. This would reduce the need to build additional plants.

Table 8-1 Summary Of Costs, Weight And Leadtime Estimates Per Glazing Alternatives

Side Window Alternative					
Issues	Existing Tempered Glass	Trilaminate	DuPont "Sentry-Glas"	St. Gobain Bilaminate	Rigid Plastic
Glazing Configuration	Single pane of 4mm tempered glass	PVB core sandwiched between annealed glass	Laminates on single ply of tempered glass	Laminates on single ply of tempered glass	Single pane of polycarbonate with abrasion resistant coating applied to both sides
Raw Glass Specification	4 mm annealed glass	Two layers of 1.85 mm annealed glass	3.28 mm tempered glass	3.28 mm tempered glass	NR
Composite/Laminate/ Polymer	NR	0.762 mm layer of Polyvinyl Butyral	0.762 mm Polyvinyl Butyral. 0.254 mm polyester with hard coating	Two layers of Polyurethane totaling 1.00 mm thickness	4 mm thick injection molded polycarbonate--polysiloxene coating applied to both sides
Processing Cost	$3.84	$10.63	$7.05	$7.14	$9.90
Material Cost	$1.40	$4.64	$9.08	$9.28	$10.00
Encapsulation Cost	NR	$6.48	$6.48	$6.48	$6.48
Abrasion Resistant Coating Cost	NR	NR	NR	NR	$6.29
Glazing Unit Cost	$5.24	$21.75	$22.61	$22.90	$32.67
Final Assembly Cost	$0.34	$0.57	$0.57	$0.57	$0.57
Installed Cost	$5.58	$22.32	$23.18	$23.47	$33.24
Leadtime	Existing	36 Months	36 Months	36 Months	36 Months
Associated Capital Investment	$624,000,000 (1)	$3,072,000,000	$2,652,000,000	$2,652,000,000	$2,865,000,000
Weight For Prototypical Window Module In LBS.	8.82	8.82	8.21	8.20	4.32

(1) This is the estimated capital investment to continue to produce tempered glass. The other estimates are all incremental costs for the production of alternative glazings.

Table 8-2 Summary Of Price Changes For Vehicles Equipped With Glazing Alternatives

	Tempered Glass		Trilaminate		DuPont "Sentry-Glas"		St. Gobian Bilaminate		Rigid Plastic	
	Per Car	Per Unit	Per Car	Per Unit	Per Car	Per Unit	Per Car	Per Unit	Per Car	Per Unit
Wholesale Price	$28.56	$7.14	$114.24	28.56	$118.68	29.67	$120.16	30.04	$170.20	42.55
Suggested Retail Price	$32.04	$8.01	$128.04	32.01	$133.04	33.26	$134.72	33.68	$190.80	47.70
Incremental Price To Consumer	$0.0(2)	$0.0	$96.00	24.00	$101.00	25.25	$102.68	25.67	$158.76	39.69

(2) Since tempered glass is used as the existing glazing in today's automobiles there is no incremental cost for its use. The absolute cost of tempered glazing is the same as the suggested retail price. The price per car is based on a four door 1995 Ford Taurus.

However, to conform existing plants, funds would have to be applied for the purchase of equipment and tooling. The total capital investment for bilaminate glazing shown in Table 8-3 includes the capital investment for production of tempered glass and the incremental investment needed to convert existing tempered glass glazing production into bilaminate glazing production. It is estimated that $780 million will be needed in addition to the $624 million currently being spent on capital investments in the glazing industry to produce enough bilaminate to supply the automobile industry. The total capital expenditures to produce bilaminate glazing is more than that to produce rigid plastic glazing; however, the initial outlay of capital to produce a bilaminate would be less than that to produce a rigid plastic glazing.

Estimates of increases in capital investment (plant and buildings, equipment and tooling) for each industry analyzed are listed in Table 8-3. The table presents a total projected investment per industry given a depreciation rate of 10 years for plant and buildings and 7 years for equipment. Tooling is amortized over a 3 year period. Given these totals and depreciation rate a per unit capital investment cost was derived. It can be seen from this table that producing laminated side windows would require the most capital outlay, followed by bilaminates and rigid plastic.

It is estimated that automobile manufacturers will have increases in capital investment associated with equipment and tooling needed to install either alternative glazing design. Incremental equipment cost ($96,000,000) will be to purchase roll formers and press benders. Incremental tooling costs ($128,000,000) will be for the purchase of forming dies. A total outlay of $224,000,000 is estimated to be spent by automobile manufacturers for equipment and tooling to install either alternative glazing design. No estimates were derived for sunk cost. The cost of replacing tooling and equipment with a useful life with necessary new equipment and tooling.

Table 8-3   Summary Of Capital Investment Per Industry (3)

Industry	Plant And Building		Equipment		Tooling		Total Projected Investment	
	Total	Per Unit	Total	Per Unit	Total	Per Unit	Total	Per Unit
Encapsulation	$256	$1.60	$640	$5.71	$128	$2.66	$1,024	$9.97
Abrasion Resistant Coating	$320	$2.00	$80	$0.71	$20	$0.42	$420	$3.13
Laminated Side Window	$640	$4.00	$1,024	$9.11	$160	$5.33	$1,824	$18.44
Bilaminate (DuPont Sentry-Glas)	$364	$2.27	$858	$7.66	$182	$3.79	$1,404	$13.73
Bilaminate (St. Gobain)	$364	$2.27	$858	$7.66	$182	$3.79	$1,404	$13.73
Rigid Plastic	$380	$2.37	$665	$5.94	$152	$3.17	$1,197	$11.48

(3) Totals are in millions. Per Unit costs in this table are cost associated with the production of one vehicle

8.7 Leadtime

Figures 8-1, 8-2 and 8-3 represent the estimated leadtime necessary for producing each alternative glazing reviewed in this study and estimated leadtime for the automobile industry to design and build automobiles which use an alternative glazing in side windows. It is estimated that 30 months is adequate leadtime to manufacture enough glazing to supply the automotive industry. This estimate assumes that the establishment of flat glass suppliers; the securing or producing of a laminated film or the developing of resin sources; the planning and construction of facilities; the order and receiving of equipment and the designing and building of tooling all begin simultaneously.

The encapsulation process can not begin until the encapsulators learn the auto assembly designs for their side windows. Once this information is received it is estimated that glazing encapsulators will require a year and a half before they will be able to meet the automobile industry's demand for encapsulated windows. Abrasion resistant coating sources are estimated to require 27 months leadtime to provide enough resistant coating to the automobile industry if rigid plastic glazing is used in side windows.

8.8 Conclusion

Research to date concludes that the alternative glazing analyzed will require capital investment outlays between $780 million and $1.824 billion by glazing manufacturers to produce side window glazing for the automobile industry. Consumers will pay between $96.00 and $158.76 to own an automobile equipped with one of the alternative glazings analyzed. Vehicles equipped with rigid plastic will be approximately 18 pounds lighter than vehicles equipped with tempered glass. And the automotive industry should be able to incorporate the use of alternative glazing in side windows within 36 months.

9. BENEFITS

This section estimates the safety benefits of installing encapsulated advanced glazing in the front side windows of light vehicles. A sequential, systematic approach is followed in deriving the benefits estimate. The estimating procedure consists of the following steps:

1. Conduct a hardcopy analysis of specific accidents in the NASS database to assess structural damage incurred in ejection crashes and attempt to reach conclusions as to whether advanced glazing would have remained in place so as to prevent ejection.

2. Conduct a case-by-case review of detailed vehicle damage data in automated NASS files and, drawing on conclusions from the hardcopy analysis, establish a case-by-case procedure for estimating whether advanced glazing would have remained in place during the crash.

3. Apply the results of step two to estimate the total number of ejections by various segregations that occurred in vehicles in which advanced glazing would have remained in place. It is the occupants of vehicles in these types of crashes that occur in the future that stand to benefit from installation of advanced glazing. The primary table presenting these data includes the following segregations:

   Degree of ejection
   Driver vs. passenger ejections
   Restraint usage
   Injury severity

4. Estimate the number of fatalities and nonfatal serious injuries that would be prevented by preventing ejection.

5. Redistribute the estimated fatal and nonfatal serious injuries that would be prevented to less serious injury levels.

6. Estimate the safety benefits of ejection-preventing front side window glazing by subtracting the projected (mitigated) injury severity distribution from the present injury distribution.

The estimation of benefits following this sequential approach follows:

9.1 Hardcopy Analysis of Ejection Cases

9.1.1 Purpose

The purpose of the analysis is to assess structural damage (such as the roof, roof header, window frame and A & B-pillars) in the ejection area of vehicles in real-world crashes. Ultimately, evaluate the difficulties the alternative glazings may encounter in retaining occupants whose vehicles have significant roof and/or door frame deformations. The analysis is limited to assessing potential retention capabilities of alternative glazings.

9.1.2 Case Selection

A significant number of fatalities and serious injuries involved the partial or complete ejection of occupants through the doors or side windows. These ejections were largely through the front-side windows and doors. The study was restricted to occupants that were completely and fatally ejected through front-side windows in rollover and non-rollover towaway crashes.

The 1988 - 1992 National Accident Sampling System Crashworthiness Data System (NASS CDS) data include 383 occupants in light passenger vehicles (cars, light trucks and multipurpose vehicles) that were completely ejected through front-side windows in towaway crashes.

Seventy-eight (6,309 national estimate[1]) were fatally injured. Fifty-one (2,503 national estimate) light truck and van occupants were fatally injured. The structural damage sustained by the vehicle was evaluated for a portion of these cases.

[1] National estimates in this paragraph are based on NASS data between 1988 - 1992.

The hardcopy study consisted of 101 fatal occupant cases. NASS 1988 - 1992 data file contains 51 LTV cases of fatally injured occupants that were completely ejected through front-side glazings. All 51 cases were selected for evaluation. The 50 passenger car cases were randomly selected.

9.1.3 Analysis of Fatal Cases

In evaluating the structural damage to the vehicle, the following points should be recognized. First, the NASS investigators typically cannot determine exactly when the occupant was ejected during the accident sequence. In vehicle crashes that involve multiple impacts it is typically difficult to determine when the occupant was ejected. In a rollover crash it is even more difficult to determine the specific ¼-turn in which an occupant was ejected. Second, the actual structural damage at the time of ejection is unknown. The vehicle damage available to the investigator is the final damage.[2] The vehicle structure usually undergoes extensive elastic and plastic deformations during the accident sequence. The NASS hardcopy slides provide an indication of crash severity. These slides also provide information about the ejection area which is used in this study.

NASS study cases that indicate occupant ejection through glazing of a door that opened during the accident sequence are omitted. Also, occupants ejected through opened windows are omitted. Twenty-three PC and LTV fatal occupant cases were omitted from evaluation due to either door openings along the ejection path or ejection through an opened window. Thus, 37 PC and 41 LTV occupant cases were evaluated.

9.1.4 Passenger Car Occupants

Thirty-seven PC fatal occupant cases were analyzed. Ten of these occupants were involved in non-rollover towaway crashes. The remaining 27 occupants were involved in rollover crashes.

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[2] NASS investigators are trained to look for post-accident damage (i.e., windshield, door, steering wheel removal, prying of doors, etc.) incurred to release entrapped occupants.

The non-rollover cases typically had less structural damage than the majority of the rollover cases. The structural damage varied in non-rollover crashes depending largely on the actual accident sequence and objects contacted. Single vehicle non-rollover collisions typically involved trees, poles and traffic barrier type of impacts.

The structural damage evaluation included damage in the area of the ejection. This included the roof, roof header, window frame, door frame, A-pillar and B-pillar. Structural damage ranged from no significant damage to extensive damage in the ejection area. For example, in the cases with no significant damage, the window frame portion of the door would be completely intact or would have

some bowing at the base from occupant contact (See Figure 9.1). In some cases the upper portion of the window frame would be slightly bent away from the roof header. In these cases, a high-penetration-resistant material could have retained the occupant.

Figure 9.1 Frame Intact

In "moderately" deformed window frames ejection mitigation would vary depending on the elastic properties of the glazing material. In cases with minimal bowing at the window base, some glazing would be more "forgiving" than others. For cases in which the roof shifts rearward and the A-pillar also rotates rearward and downward, the glazing must possess some degree of

Figure 9.2 Stretching of A-Pillar & Roof Header

resilience to maintain its properties and ultimately retain the occupant (See Figure 9.2).

The extensively deformed window frames generally were non-addressable. In these cases, the window portion of the door frame (that would retain the glazing) was destroyed. The window structure was typically twisted, bent and/or torn. These collisions were typically very severe and catastrophic in nature (See Figure 9.3).

Figure 9.3 Non-Addressable

9.1.4.1 Subjective Analysis of Structural Damage

To better assess the applicability of alternative glazings as a solution to ejection mitigation, a qualitative analysis was performed. The following assumptions were made in performing this analysis.

- The physical damage shown in the slides is similar to or the same as the physical conditions present during the ejection occurrence.

- The alternative glazings have some degree of resilience (maybe similar to windshield glass-plastic) to retain the occupant.

- The alternative glazing is designed to stay intact during moderate deformations of the window frames (e.g., an encapsulation).

Based on the above criteria, the cases were classified as addressable, possibly addressable and non-addressable[3] (See Figures 1, 2 & 3, respectively). The "addressable" category included cases in which the window structure of the door frame was still intact. The window frame was typically

[3] This analysis is limited to determining whether the occupant would have been retained by alternative glazings. Survivability is later addressed.

in its original shape. The "possibly addressable" category included cases in which there was considerable bowing at the window base and/or deflection and deformation of the roof, roof header, A-pillar and/or B-pillar. These cases were highly dependent on the resilience of the alternative glazing. The more resilient the material, the more resistance is allowed. These cases would be considered "addressable" if an alternative glazing was in-place that could manage the deformations and maintain ejection mitigating properties. The "non-addressable" cases were typically vehicles containing extensive structural damage to the window frame. This category included cases in which the window frame was destroyed.

Of the 37 NASS PC cases, 20 were considered addressable, seven were possibly-addressable, and ten were non-addressable. Given the appropriate glazing material there were potentially 27 addressable cases.

9.1.5 Light Truck and Van Occupants

Forty-one fatal light truck and van occupants were evaluated. Eight of these occupants were involved in non-rollover towaway crashes. The remaining 33 occupants were involved in rollover crashes.

The structural damage in non-rollover crashes was typically less severe than the rollover cases. Typical structural damage consisted of the window frame bending away and downward from the roof header (ranging approximately from 45° to 135° degrees). Vehicles involved in rollover crashes typically experienced extensive roof crush/shifts and intrusion into the occupant compartment. There was also some bowing at the base of the window frame.

The structural damage ranged from no significant damage to extensive damage in the ejection area. For example, in a non-rollover side impact collision the lower door frame would typically experience the most damage while the window frame would still be intact. In some cases, a heavily intruded lower door frame would result in the upper window frame bending away from the roof header. In the majority of the NASS rollover cases, the A and B pillars typically shifted causing the roof to collapse into the occupant compartment.

Ejection appears to be preventable in the cases with minimal structural damage to the roof, window and door frame, in the ejection area. The cases in which the A and/or B pillar shift, ejection mitigation will vary depending on the alternative glazing properties. Vehicles involved in four or more ¼-turns typically experienced extensive structural damage.

9.1.5.1 Subjective Analysis of Structural Damage

The "addressable" category included cases in which the window structure of the door frame is still intact. The window frame may be slightly bent outward away from the roof header but still in its original shape. The "possibly addressable" category included cases in which there was considerable bowing at the base at the window base, deflection of the roof header and/or the A and B pillars. The "possibly addressable" category also included cases in which the A and B pillars collapsed (minimally) towards each other causing the roof header to collapse downward into a V-shape (see Figure 9.4).

Should the A and B pillars experience a similar but more extensive deformation of the roof header, the case would then be classified as "non-addressable" (See Figure 9.5). The "non-addressable" cases are typically vehicles containing extensive structural damage to the window frame.

Figure 9.4 Possibly Addressable

Of the 41 NASS LTV cases, 17 were considered addressable, seven were possible-addressable, and 17 were non-addressable. Given the appropriate glazing material there were potentially 24 addressable cases.

Figure 9.5 Non-Addressable

9.1.6 General Summary

Structural damage included bowing at the window base, deformation and deflection of the Apillar and roof headers. There was an increase of roof crush into the occupant compartment in rollover collisions. Pickup trucks tended to experience increased occurrence of roof crush into the occupant compartment. Pickup trucks also tended to experience more deflection and deformation of the A and B pillars.

9.1.6.1 Subjective Analysis of Structural Damage

Of the 78 NASS light passenger vehicle cases, 37 cases were considered addressable, 14 were possibly addressable and 27 were non-addressable. Twenty-seven of the 37 PC cases were **potentially** addressable. Twenty-four of the 41 LTV cases were **potentially** addressable (See Table 9.1). Ejection mitigation is possible given the appropriate alternative glazing. Again, the glazing must possess some degree of resilience to maintain its properties and ultimately retain the occupant.

Table 9.1 Results of Subjective Analysis

FATAL OCCUP	ACCIDENT TYPE	ADDRESSABLE	POSSIBLY ADDRESSABLE	NON-ADDRESSABLE	TOTAL
PC	Non-R/O	6	1	3	10
	Rollover	14	6	7	27
LTV	Non-R/O	2	--	6	8
	Rollover	15	7	11	33
TOTAL		37	14	27	78

The analysis performed represents a worst case scenario in relation to the amount of structural damage at the time of ejection. That is, if all ejections took place at the conclusion of the crash event, the structural damage would be as seen by the investigator. If the ejection took place earlier in the event, presumably there would be less structural damage. Therefore, in actuality there would probably be a higher percentage of cases that could be "addressable" through the use of alternative glazings.

9.2 Hardcopy Comparative Analysis

9.2.1 Collision Deformation Classification (CDC)

The hardcopy study cases were used as a template to extend alternative glazing retention capabilities to the remaining automated ejection cases. Ejection-preventing glazings start losing their countermeasure value as damage severity increases in one or more crush areas. Severe damage not only results in broken and missing glazing but also in loss of integrity of the basic structure of the vehicle. The Collision Deformation Classification (CDC) codes of the NASS study cases were evaluated to determine their suitability as criteria for estimating whether the advanced glazing would have remained in place. The CDC classification system consists of seven characters arranged in a specific order. Each character describes specific deformation detail concerning the direction, location, the size of the area, and extent, which combined together form a descriptive composite of the damaged vehicle.

The automated CDC, primary and secondary, codes are not necessarily--and many were not--related to the ejection area. The automated CDC codes describe the two most severe damage areas. These damage areas are not necessarily in the ejection area. Another limitation of the CDC was the lack of specific roof damage information. For example, in the rollover cases the "top damage" code was not specific enough to determine whether the roof damage was in the area of ejection. Rollover crashes represented a significant portion of the hardcopy study cases. Due to the limitations of the CDC, specifically for roof damage, other methods of evaluation were utilized.

9.2.2 Intrusion Codes

To better assess specific deformations related to the ejection, an analysis was performed evaluating intrusion codes in the ejection area. Related intruding components included the NASS variables: roof, roof side rail, window frame, A-pillar and B-pillar. Cases that had no intrusion in the ejection area were coded as "no related intrusion." The intrusion codes (related to the ejection area) for each of the study cases were evaluated. For each case, the magnitude of intrusion of the most intrusive component was selected. Once the maximum magnitude of intrusion for each study case was established, the cases were evaluated within the appropriate category (i.e. *addressable, possibly addressable & non-addressable*).

In describing the magnitude of intrusion, the NASS intrusion variable uses the following ranges:

1 = 3 - 8 cm	5 = 46 - 61 cm
2 = 8 - 15 cm	6 $\geq$ 61 cm
3 = 15 - 30 cm	7 = Catastrophic
4 = 30 - 46 cm	8 = Unknown

In evaluating the maximum intrusive damage, the *roof* variable was not specific enough in describing the damage in the ejection area, near the window frame. As a result, the *roof* variable was omitted from the group of related intrusion codes (listed above).

Each case was tallied according to its, respective, category and maximum intrusion. After evaluating the 78 hardcopy cases, with respect to the various categories and intrusion, the following distribution was devised.

Maximum Magnitude of Intrusion (cm)	Projected Rate of Retention for the Advanced Glazing
No relevant intrusion: (see explanation below)	
Rollover	0.667
Non-rollover	0.750
3 - 8	1.000
8 - 15	0.750
15 - 30	0.500
30+	0.000

Cases with “no related intrusion” encompassed a broad spectrum of damage and non-damage scenarios. These cases ranged from the addressable to non-addressable categories. An addressable cases with “no related intrusion” had minor or no damage at all in the ejection area. However, the possibly- and non-addressable cases with “no related intrusion” tended to experience non-intrusive damage in the ejection area. For example, the possibly addressable case could experience damage patterns, such as, outward bowing at the lower portion of the window frame (typically, due to occupant loading). Or, portions of the window frame could separate, bending away from the roof side rail, A-pillar, etc. The non-addressable cases with “no related intrusion” were cases with the window frame extensively damaged--twisted/torn. Typically, there was extensive bowing at the base of the window frame. These cases were, typically, involved in multi-impacts.

The appropriate fraction above is multiplied times the expansion factor (weight) for each NASS case. The sum of this procedure for all cases is an estimate of the annual number of ejections out front side windows for which the encapsulated advanced glazing would have been retained in the crash.

9.3 Estimate the Number of Occupants Ejected in Crashes in Which Advanced Glazing Would Hold

The results obtained in the Section 9.2 analysis were used to estimate the number of ejections out front side windows of light vehicles that would be prevented by advanced glazing. The procedure was to multiply the fraction indicated for each of the degrees of intrusion of relevant intruding components for each crash type (this fraction indicating the portion of ejection crashes for which it was deemed that advanced glazing would have remained in place during the crash) times the expansion factor (weight) for each NASS front-side-window ejection case. (All cases in which the ejection window had been open or the door containing the ejection window had opened during the crash were excluded.) The sum of the results of applying this procedure to the NASS cases is an estimate of the annual number of ejections out front side windows for which encapsulated advanced glazing would have been retained in the crash. The data can be sorted or tabulated in various ways.

Table 9.2 presents the estimated annual number of ejections through front side windows of light vehicles in which encapsulated advanced glazing would have remained in place, by degree of ejection (complete or partial), seating position (driver or passenger), whether a safety belt was used, and injury severity by the Abbreviated Injury Scale (AIS) classification system.[4] The injury levels reported in the table are the maximum injury levels, or MAIS's. As indicated, a total of 11,277 occupants ejected out front side windows were in vehicles in which it was deemed that advanced glazing would have remained in place during the crash had the vehicles been so equipped. This represents 45 percent of all occupants ejected out front side windows

[4] Following are injury descriptors for the Abbreviated Injury Scale:

AIS 0 = no injury
AIS 1 = minor
AIS 2 = moderate
AIS 3 = serious
AIS 4 = severe
AIS 5 = critical

Table 9.2
1988-1993, Estimated Annual Number of Ejections Through Front Side Windows of Light Vehicles in Which Encapsulated Advanced Glazing Would Have Remained in Place, by Degree of Ejection, Belt Use, Seat Position, Inj. Sev.

	Complete Ejections			Partial Ejections			Total Ejections		
	Restraint Usage			Restraint Usage			Restraint Usage		
	Yes	No	Total	Yes	No	Total	Yes	No	Total
DRIVER									
MAIS=0	0	20	20	0	56	56	0	76	76
MAIS=1	0	743	743	502	1755	2257	502	2498	3000
MAIS=2	37	905	942	583	818	1401	620	1723	2343
MAIS=3	6	641	647	164	276	440	170	917	1087
MAIS=4	0	58	58	6	45	51	6	103	109
MAIS=5	0	133	133	34	179	213	34	312	346
FATAL	145	727	872	168	602	770	313	1329	1642
TOTAL	188	3227	3415	1457	3731	5188	1645	6958	8603
PASS.									
MAIS=0	0	0	0	0	0	0	0	0	0
MAIS=1	9	557	566	183	188	371	192	745	937
MAIS=2	0	497	497	116	192	308	116	689	805
MAIS=3	3	259	262	22	144	166	25	403	428
MAIS=4	0	25	25	0	3	3	0	28	28
MAIS=5	0	19	19	16	8	24	16	27	43
FATAL	66	133	199	119	115	234	185	248	433
TOTAL	78	1490	1568	456	650	1106	534	2140	2674
DRIV&PASS									
MAIS=0	0	20	20	0	56	56	0	76	76
MAIS=1	9	1300	1309	685	1943	2628	694	3243	3937
MAIS=2	37	1402	1439	699	1010	1709	736	2412	3148
MAIS=3	9	900	909	186	420	606	195	1320	1515
MAIS=4	0	83	83	6	48	54	6	131	137
MAIS=5	0	152	152	50	187	237	50	339	389
FATAL	211	860	1071	287	717	1004	498	1577	2075
TOTAL	266	4717	4983	1913	4381	6294	2179	9098	11277

annually (11,277/24,782). Of the estimated 11,277 occupants whose ejections are estimated to be preventable, as indicated, 8,603 were drivers, 2,674 passengers; 6,294 were partially ejected, 4,983 completely ejected; 2,179 were usinga safety belt, 9,098 were not. A total of 2,075 of the ejectees (18%) were fatally injured; 2,041 incurred nonfatal serious injuries (MAIS 3+); 7,085 incurred minor or moderate injuries (MAIS 1, 2); and 76 ejected occupants were uninjured.

9.4 Estimate the Number of Fatalities and Nonfatal Serious Injuries That Would Be Prevented

The next step is to estimate the number of fatalities and nonfatal serious injuries that would be prevented as the result of advanced glazing preventing ejection. A statistical approach was employed to estimate the reduction in the risk of a fatality and nonfatal serious injury. The results of this analysis were applied to the preceding estimates of ejection and accompanying injury levels to estimate the number of fatalities and nonfatal serious injuries that would be prevented.

The methodology employed estimates of the relative risk of death and injury for ejected occupants of motor vehicles compared to non-ejected occupants and the reduction in fatalities and serious injuries if ejection were eliminated.

9.4.1 Matched-pair Analysis of Reduction in Risk of Fatality and Nonfatal Serious Injury from Preventing Ejection

9.4.1.1 General Description of the Estimation Procedure

The basic statistical methodology utilized is the double-pair comparison method as described by Evans (1986), also known as matched-pair analysis. This methodology allows one to obtain comparisons of fatality rates (or serious injury rates) between ejected and non-ejected occupants in crashes of the same severity. Crash severity has to be taken into account, since ejections tend to take place in crashes of higher severities. The following section is devoted to an exposition of the double comparison method and some related approaches to the study of fatality and injury distributions among ejected and non-ejected occupants.

The data analyzed were obtained from the Fatal Accident Reporting System (FARS) and the State Data files. Both databases are maintained by the National Center for Statistics and Analysis (NCSA). FARS data contain information on virtually all crashes involving a fatality in the country since 1975, and as such are the most comprehensive source of information for studying fatal accidents. The State Data files are records of police accident reports from some 17 states, which are provided to NCSA annually by states participating in the program. The files are quite an extensive collection of traffic accident data, since they supposedly contain all police-reported accidents. They can be used for studying both fatal crashes as well as crashes of lesser severities. The results of the analysis and conclusions are summarized below.

9.4.1.2 Double-pair Comparison Method And Related Techniques

The double pair comparison method is a statistical technique designed to study the effect of some characteristic of individuals involved in motor vehicle crashes on the consequences of the crashes to those individuals. To use the method, a collection of data is needed which contains information on the characteristics of interest for all individuals involved in the type of crashes studied as well as the outcomes of the crashes for these individuals. The method was originally applied to study the effect of using or not using safety a belt at the time of a crash (individual characteristic) in terms of whether the crash was fatal to the individual (crash outcome). The original work is Evans (1986a, b), see also Sikora (1986).

The effect of the factor (or characteristic) studied is assessed through an estimate of the ratio of the probability of being subjected to the outcome under investigation when the individual in the crash has the characteristic of interest to the probability of that outcome for individuals without the characteristic. For example, in the studies of the effectiveness of safety belt use, “fatality risk ratio” was estimated, which is the ratio of the probability of death for belted drivers in a fatal crash to the death probability for unbelted drivers in the same type of crash.

The difficulty in obtaining such estimates is the lack of an obvious measure of exposure to risk for belted and unbelted drivers against which the death counts could be compared. The method of double-pair comparison uses the information on passengers of the cars involved in the crashes to produce the required exposure estimates (for the drivers). In the discussion that follows, a passenger is always understood to mean a front seat passenger.

In the context of estimating fatality risk for ejected versus non-ejected drivers, we can use the data on ejected passengers of cars involved in fatal accidents in the normalizing role (Evans, 1989). Thus, we look at all, say N_1, pairs of ejected drivers and non-ejected passengers in our database and at all, say N_2, pairs of non-ejected drivers and ejected passengers. We then count the number of driver fatalities, say d_1, among the N_1 pairs of ejected drivers and ejected passengers, and the number of passenger fatalities, say p_1 among the same N_1 pairs. Then d_1/N_1 is a rough estimate of the probability of death of an ejected driver traveling with ejected passenger and p_1/N_1 is a rough estimate of the probability of death of an ejected passenger traveling with an ejected driver. Similarly, if d_2 denotes the number of fatalities among the N_2 non-ejected drivers traveling with ejected passengers and p_2 is the number of fatalities among passengers in the same accidents, then d_2/N_2 estimates the death probability for the non-ejected driver and p_2/N_2 represents the death probability of an ejected passenger.

Consider the fatality ratio $r_1 = \frac{d_1}{p_1} = \frac{d_1/N_1}{p_1/N_1}$, which can be interpreted as the ratio of the probabilities of death for ejected driver and ejected passenger. Note that this ratio could be viewed as a measure of relative risk of death for drivers versus passengers in ejection. Now consider the fatality rate $r_2 = \frac{d_2}{p_2} = \frac{d_2/N_2}{p_2/N_2}$, which is interpreted as the ratio of the probabilities of death for non-ejected driver and ejected passenger. If the only factor affecting the probability of death in the population of motor vehicle occupants under consideration is ejection, then the probability of death for non-ejected passengers is the same regardless of whether the driver is ejected of not. Under this assumption (since p_1/N_1 and p_2/N_2 both estimate the same quantity), the ratio $R = \frac{r_1}{r_2} = \frac{d_1/p_1}{d_2/p_2}$ estimates the ratio of the probabilities of death for the ejected driver and the non-ejected driver, which is the relative risk of main interest.

The above argument ignores the fact that death probabilities depend on crash severity, and crash severities may have different distributions among ejected and non-ejected drivers (and passengers). Evans (1986) addresses this problem (discussing it in terms of belted and unbelted occupants, rather than ejected and non-ejected ones), and presents a mathematical formulation which allows him to argue that even if the distribution of crash severities for belted and unbelted drivers are different, the method can be expected to produce reasonable estimates of the risk ratio R.

One notices that in using ejected passengers to normalize for exposure to risk, the crashes under consideration become restricted to those involving at least one ejection, and thus the severities of these crashes may not vary too much. In that case, the assumptions on which the double-pair comparison method relies are more likely to be satisfied.

Non-ejected passengers can also be used in the exposure normalizing role. In that case, crashes involving no ejections enter into consideration and it is more difficult to justify the approach. However, it turns out that both estimates of the relative risk R are usually similar.

Furthermore, the roles of drivers and passengers can be reversed, so that drivers can be used in the normalizing role in estimating relative risk of death for ejected versus non-ejected passengers. The formula for the relative risk using ejected drivers as controls is $R=\frac{r_3}{r_4}$,

where $r_3=\frac{p_3}{d_3}$, $p_3=p_1$ - number of fatalities among ejected passengers traveling with ejected drivers, $d_3=d_1$ - number of fatalities among ejected drivers traveling with ejected passengers, $r_4=\frac{p_4}{d_4}$, p_4 - number of fatalities among non-ejected passengers traveling with ejected drivers, d_4 - number of fatalities among ejected drivers traveling with non-ejected passengers. Finally, the same relative risk can be estimated using non-ejected drivers as controls.

Considering the uncertainties inherent in the method of estimation, in addition to the random nature of the fatality counts, any estimate of the standard error of the relative risk ratio R can only be expected to be a tentative assessment. The approach of Evans (1986) is to decompose the standard error σ_R^2 into two terms as follows $\sigma_R^2=\sigma_1^2+\sigma_2^2$, where σ_1^2 is to account for the imprecision intrinsic to the method itself, and σ_2^2 is due to the sampling error. The former is (based on judgement and experience) taken by Evans to be $\sigma_1^2 = 0.1$, and the later is calculated, using the method of propagation of errors, under the assumption that the counts d_1, p_1, d_2, p_2, etc., follow the Poisson distribution, which leads to $\sigma_2^2=R^2\left(\frac{1}{d_1}+\frac{1}{p_1}+\frac{1}{d_2}+\frac{1}{d_2}\right)$. The estimates of standard errors presented in this paper are obtained using the above method.

Both ejected and non-ejected passengers can be used as controls for risk exposure in estimating the ejected to non-ejected driver fatality risk ratio. The issue of combining these estimates then arises. As suggested in Evans (1986), a weighted average of the estimates can be used, with weights inversely proportional to the standard deviations, however, applied to the logarithms of the R's, which is then converted to the original scale by exponentiating.

The ratio of the risk of death if ejected to the risk of death if not ejected, R, can be used to estimate the fraction of fatalities that would be prevented by eliminating ejection. The approach of Evans (1986) is based on the assumption that if ejection were eliminated, then motor vehicle occupants who were originally ejected would be exposed to the same risk of death as those occupants who were not ejected in similar crashes. That is, we assume that ejection-preventing mechanism, such as advanced glazing, will not contribute to fatality risk more than to bring it to the level of risk for occupants not ejected regardless of whether ejection preventing mechanism is present or not. This can be justified by pointing out that in a crash severe enough to result in an ejection, the occupant not ejected is most likely contained in the vehicle by such elements of the vehicle interior as pillars, dashboard, steering wheel, door frame, etc. The modeling sumulations presented above indicate that the most serious injury-producing contacts would be with parts of the vehicle interior other than the advanced glazing itself. This finding is consistent with the injury-reduction estimation procedure presented herein.

Under the above assumptions, a straightforward argument shows that a fraction of ejected fatalities (in a given population of motor vehicle occupants, such as unrestrained drivers of passenger cars) that will be prevented by eliminating ejection is $f = 1 - \frac{1}{R}$. The standard error of f can be calculated, using the method of propagation of errors, as $\sigma_f^2 = \sigma_R^2 / R^4$.

The method can equally well be applied to the data on non-fatal accidents to estimate the benefits of advanced glazing in serious injury prevention. The role of fatalities in the above discussion is now played by the seriously injured. One could also look at minor injury prevention benefit of advanced glazing by restricting the analysis to the crashes with no deaths or serious injury, etc., however, the numbers of individuals suffering only minor or no injuries in ejections is small, and the estimates become unreliable.

In the analysis presented below, complete ejections and partial ejections were treated separately, and distinct estimates were obtained for fractional reductions in fatalities and injuries based on the data on crashes involving complete ejections and partial ejections. Additionally, restrained and unrestrained populations of motor vehicle occupants were treated separately.

9.4.2 Estimation of Fatality and Nonfatal Serious Injury Reduction

Estimates of the reduction in the risk of fatal and nonfatal serious injury derived in the previous section using the matched-pair technique were applied to the estimates of ejections in crashes in which it was deemed that advanced glazing would have remained in place during a crash, as reported in Table 9.2. The matched-pair analysis described above derived specific estimates of the increase in risk of fatal and nonfatal serious injury for driver and passenger, complete and partial ejection, restraint use and nonuse. The following presentation illustrates how the matched-pair technique was employed to estimate the reduction in fatal and serious injuries for drivers who were partially ejected and who were not wearing seat belts. The injury distribution for such ejected occupants as presented in Table 9.2 is:

MAIS=0	276
MAIS=1	1755
MAIS=2	818
MAIS=3	276
MAIS=4	45
MAIS=5	179
FATAL	602
TOTAL	3731

The matched-pair estimate of the increase in risk of fatality of being ejected was 3.477 (driver partially ejected, no restraint). It follows that the reduction in the risk of fatality from preventing ejection is 1-1/3.477 or 0.712. The reduction in fatalities was therefore estimated to be 0.712 X 602 = 429 fatalities prevented. (The redistribution of these prevented fatalities to lower injury levels is presented in the next section.)

The reduction in serious injuries was similarly estimated. From State accident data, the matched-pair approach estimated the risk of receiving an "A" level or "incapacitating" injury (serious injury here) as rated under the KABCO system used by the States.[5] The matched-pair estimate of the increase in risk of nonfatal serious injury of being ejected was 2.312. The reduction in the risk of serious injury from preventing ejection is 1-1/2.312 or 0.567. As in estimating the fatality reduction, the next step is to multiply the number of "A" injuries by this fraction to estimate the reduction in these injuries. First, however, the above tabulation of injuries rated by the MAIS scale must be converted to its KABCO equivalent to obtain the estimated number of "A" injuries to which to apply the reduction factor. To do this, conversion factors were used based on an analysis of data collected under the agency's National Accident Sampling System over the 1982-1986 period. This analysis compared the KABCO injury levels, as indicated on police accident reports, to MAIS levels, as determined by NASS investigation teams for the same accidents. The cross distribution of MAIS and KABCO injuries and the respective factors to apply to convert one rating system to the other are presented in Table 9.3.

Using the conversion factors in Part 2 of Table 9.3, the injury distribution of drivers who were not wearing seat belts and were partially ejected is converted from the MAIS system to the KABCO system:

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[5] The "KABCO" injury severity rating system is:

A = Incapacitating injury
B = Nonincapacitating injury
C = Possible injury
K = Killed
No = No injury
ISU = Injured, but severity unknown
UNK = Unknown if injured

Table 9.3
KABCO/MAIS Injury Rating Systems

Part 1
KABCO/MAIS Injury Distribution Table
1982-1986 NASS Injuries

MAIS	A	B	C	K	NO	ISU	UNK
0	34125	251763	1313849	2243	55920352	16197	567577
1	1106880	4039582	4731293	2899	4493704	151977	111255
2	628338	636692	445949	1188	125755	33822	11258
3	376136	153411	99524	238	17347	9352	5431
4	65427	13620	4229	394	716	3688	139
5	39650	3518	1219	0	0	288	310
FATAL	12194	1350	645	168780	60	819	0
TOTAL	2262750	5099936	6596708	175742	60557934	216143	695970

A = Incapacitating injury
B = Nonincapacitating injury
C = Possible injury
K = killed
No = No injury
ISU = Injured, but severity unknown
UNK = Unknown if injured

MAIS 0 = No injury
MAIS 1 = Minor
MAIS 2 = Moderate
MAIS 3 = Serious
MAIS 4 = Severe
MAIS 5 = Critical
AIS = Abbreviated Injury Scale
MAIS = Maximum AIS

Part 2
MAIS To KABCO Conversion Table
1982-1986 NASS Injuries

MAIS	A	B	C	K	NO	ISU	UNK	TOTAL
0	0.00059	0.00433	0.02261	0.00004	0.96238	0.00028	0.00977	1
1	0.07562	0.27597	0.32323	0.00020	0.30700	0.01038	0.00760	1
2	0.33369	0.33813	0.23683	0.00063	0.06678	0.01796	0.00598	1
3	0.56866	0.23194	0.15047	0.00036	0.02623	0.01414	0.00821	1
4	0.74169	0.15440	0.04794	0.00447	0.00812	0.04181	0.00158	1
5	0.88140	0.07820	0.02710	0.00000	0.00000	0.00640	0.00689	1
FATAL	0.06633	0.00734	0.00351	0.91804	0.00033	0.00445	0.00000	1

Table 9.3 (CONTINUED)
Part 3
KABCO To MAIS Conversion Table
1982-1986 NASS Injuries

MAIS	A	B	C	K	NO	ISU	UNK
0	0.01508	0.04937	0.19917	0.01276	0.9342	0.07494	0.81552
1	0.48917	0.79208	0.71722	0.01650	0.07421	0.70313	0.15986
2	0.27769	0.12484	0.06760	0.00676	0.00208	0.15648	0.01618
3	0.16623	0.03008	0.01509	0.00135	0.00029	0.04327	0.00780
4	0.02891	0.00267	0.00064	0.00224	0.00001	0.01706	0.00020
5	0.01752	0.00069	0.00018	0.00000	0.00000	0.00133	0.00045
FATAL	0.00539	0.00026	0.00010	0.96039	0.00000	0.00379	0.00000
TOTAL	1	1	1	1	1	1	1

MAIS Injury Distribution		KABCO Injury Dist.	
MAIS=0	56	A	766
MAIS=1	1755	B	847
MAIS=2	818	C	811
MAIS=3	276	K	160
MAIS=4	45	NO	655
MAIS=5	179	ISU	41
FATAL*	173	UNK	22
TOTAL	3302	Total	3302

*Excludes 419 prevented fatalities

As indicated, conversion of the MAIS injury distribution to the KABCO system produces an estimated 766 "A" or serious injuries. The 766 serious injuries are multiplied by the serious injury reduction factor of 0.5674 derived using the matched-pair procedure to estimate the number of nonfatal serious injuries occurring to partially ejected nonbelted drivers that would be prevented as the result of drivers being retained inside their vehicles because of advanced glazing. The estimate of serious injuries prevented is thus 0.5674 X 766 = 435 serious injuries prevented.

Estimates of fatal and nonfatal serious injury reduction for the other breakouts in Table 9.2 -- restrained drivers partially ejected, restrained and unrestrained passengers partially ejected, and unrestrained drivers and passengers completely ejected -- were similarly derived. Fatality and serious injury reductions were not estimated for restrained drivers and passengers who were completely ejected, since they, with two exceptions (a child in a child safety seat, projected to account for nine MAIS 1 injuries; a driver wearing a lap and shoulder belt, projected to account for five MAIS 3 injuries), were wearing shoulder belts only. Shoulder belts only will not be permitted in new vehicles produced in the timeframe when any regulatory requirement for advanced glazing could be expected to be implemented. All model year 1998 and later passenger cars and model year 1999 and later light trucks must have both air bag and lap shoulder belt systems for both the driver and passenger seating positions. It is assumed that these presently restrained occupants would use their lap/shoulder belt systems in the future and would not be ejected.

Table 9.4 presents the fatality and nonfatal serious injury reduction factors derived employing the matched-pair technique and the number of fatalities and serious injuries that would be prevented for the breakouts in Table 9.2, as estimated employing the above described procedure.

Table 9.4
Reduction in the Risk of Fatal and Nonfatal Serious Injury from Preventing Ejection; Estimates of the Number of Fatalities and Serious Injuries that Would Be Prevented

Occupant Category	Increased Risk if Ejected (X)		Reduction in Risk (1-1/X)		Estimated Fatalities Prevented	Estimated Serious ("A") Injuries Prevented
	Of Fatality	Of Serious Injury	Of Fatality	Of Serious Injury		
Driver, Compl. Ejected, No restraint	3.3945 (0.9369)*	1.8759 (0.4744)*	0.7054 (0.0813)*	0.4669 (0.1348)*	513	419
Pass., Compl. Ejected, No restraint	3.1441 (0.8626)*	1.6447 (0.4178)*	0.6819 (0.0873)*	0.3920 (0.1544)*	91	154
Driver, Partially Ejected, Restraint	3.4491 (1.1167)*	1.9287 (0.5169)*	0.7101 (0.0939)*	0.4815 (0.1389)*	119	175
Driver, Partially Ejected, No Restraint	3.4768 (0.8255)*	2.3117 (0.5300)*	0.7124 (0.0683)*	0.5674 (0.0992)*	429	435
Pass., Partially Ejected, Restraint	3.3291 (1.0813)*	1.6891 (0.4513)*	0.6996 (0.0976)*	0.4080 (0.1582)*	83	33
Pass., Partially Ejected, No Restraint	3.1186 (0.7403)*	1.8890 (0.4334)*	0.6793 (0.0761)*	0.4706 (0.1215)*	78	81
Total Injuries and Fat. Prevented					1,313	1,297

* Standard error estimate

9.5 Redistribute the Estimated Fatal and Nonfatal Serious Injuries That Would Be Prevented to Less Serious Injury Levels

The next step in evaluating the potential benefits of advanced glazing is to redistribute the fatal and nonfatal serious injuries that would be prevented by preventing ejection to less serious injury levels. A matched-pair approach using State accident data was also used for this purpose. Assuming, as in the above discussion of the double-pair comparison method, that the effect of being prevented from ejection by the advanced glazing is the same as the effect of being prevented from ejection by other elements of the vehicle interior, we can approximate this distribution by the distribution of injuries among non-ejected occupants of motor vehicles in accidents involving ejections. More specifically, we can use the injury distribution among non-ejected drivers in crashes in which the passenger was ejected as an estimate of the distribution of injuries among drivers in crashes when the advanced glazing is in place. This distribution is calculated by considering the N_2 pairs of non-ejected divers and ejected passengers as above, and counting not only the fatal injuries d_2 among the drivers, but also the numbers of drivers with serious injuries a_2, minor injuries b_2, possible injuries c_2, and no injuries o_2. Then the fractions d_2/N_2, a_2/N_2, b_2/N_2, c_2/N_2, and o_2/N_2 represent the desired estimates. Note that this approach is consistent with the double pair comparison method, which relies on the same interpretation of the above fractions. By considering the crashes in which drivers are ejected and passengers are not, an analogous distribution for the passengers can be obtained. Again, an illustration of the estimation procedure is provided using data for drivers who were partially ejected and not wearing seat belts, as reported in Table 9.2.

First, the redistribution to lower injury levels of the estimated 429 fatalities that would be prevented for this category of ejection will be estimated. This entails calculation of the States' injury distribution (using the KABCO rating system) for drivers who were not ejected in crashes in which passengers not wearing restraints were partially ejected, as discussed above. The prevented fatalities are redistributed according to this KABCO distribution and then converted to the MAIS injury scale. This procedure is shown below in Table 9.5.

Table 9.5
Redistribution of 429 Fatalities to Partially Ejected, Unrestained Drivers That Would Be Prevented to Lesser Injury Levels*

Fatalities Prevented	States' Injury Dist. for Surviving Unejected Drivers in Comparable Crashes	Percent of Group	Redist. Fatalities by KABCO	Converted to MAIS Injury Scale MAIS	Redist. Fatalities
429	A	0.2533	109	0	119
	B	0.3342	143	1	226
	C	0.1712	73	2	53
	No Injury	0.2414	104	3	24
	Total	1.0000	429	4	4
				5	3
				Total	429

* An estimated 429 fatal injuries to unrestrained drivers who were partially ejected would be prevented by advanced glazing. The redistribution of these 429 fatalities to lesser injury levels is presented as an illustration of the procedure employed in redistributing to lesser injury levels all fatalities that it was estimated would be prevented.

Similarly, the "A" level or serious injuries that it was estimated would be prevented by advanced glazing were redistributed to levels "B", "C", and " No Injury" under the State rating systems. The procedure for redistributing the estimated 435 "A" level injuries that would be prevented by preventing partial ejections of restrained drivers is shown in Table 9.6. As in Table 9.5, the estimated reduction in injury based on the KABCO distribution was converted to the MAIS scale.

Table 9.6
Redistribution of 435 Serious Injuries to Partially Ejected, Unrestained Drivers
That Would Be Prevented to Lesser Injury Levels*

Serious Injuries Prevented	States' Dist. of lesser Inj. for Drivers in Comparable Crashes	Percent of Group	Redist. Serious Injuries by KABCO	Converted to MAIS Injury Scale MAIS	Redist. Fatalities
435	B	0.4475	194	0	159
	C	0.2293	100	1	237
	No Injury	0.3232	140	2	31
	Total	1.0000	435	3	7
				4	1
				5	
				Total	435

* An estimated 435 serious ("A" level) injuries to unrestrained drivers who were partially ejected would be prevented by advanced glazing. The redistribution of these 435 injuries to lesser injury levels is presented as an illustration of the procedure employed in redistributing to lesser injury levels all serious injuries that it was estimated would be prevented.

Further, as an illustration of the methodology employed for estimating safety benefits for the driver vs. passenger, degree of ejection, and restraint usage breakdowns presented in Table 9.2, Table 9.7, below, presents the calculation of the estimated new injury distribution that presently partially ejected, unrestrained drivers would experience if advanced glazing prevented their ejection. As indicated, the estimation begins with the present injury distribution (as reported in Table 9.2) and (1) deducts the fatalities that would be prevented, (2) adds the nonfatal injuries that the previously fatally injured drivers would incur (as presented in Table 9.5), (3) deducts serious ("A") injuries that would be prevented, and (4) adds lesser level injuries that drivers who had sustained the serious injuries would incur instead (as presented in Table 9.6).

Table 9.7
Partially Ejected, Unrestrained Drivers -- Estimated Number of Fatal and Serious Injuries Prevented and Their Redistribution to Lesser Injury Severity Levels

MAIS	Present Injury Distribution	Less Fatalities Prevented	Plus Redist. Prevented Fatalities	Less "A" Injuries Prevented*	Plus Redist. "A" Inj.	Est. New Injury Dist. with Ejections Prevented
0	56		119	7	159	327
1	1755		226	212	237	2006
2	818		53	121	31	781
3	276		24	72	7	235
4	45		4	13	1	37
5	179		3	10	0	172
Fatal	602	429	0	0	0	173
Total	3731		429	435	435	3731

* Data in Table 9.3 were used to distribute the estimated 435 serious injuries that would be prevented by the MAIS rating system.

The same procedure as presented above in estimating injury reduction for unrestrained drivers who were partially ejected was used in estimating safety benefits for the other breakouts of ejected occupants reported in Table 9.2. Table 9.8 presents the present injury distribution, the estimated new injury distribution reflecting the redistribution of fatalities and serious injuries that would be prevented to lower injury levels, and the differences between the two distributions, which are the estimated safety benefits.

Table 9.8
Estimated Safety Benefits of Advanced Glazing,
Segregated by Driver vs. Passenger, Degree of Ejection,
and Restraint Usage

	MAIS	Present Injury Distri-bution	Est. Injury Distribution with Ejection Prevented	Difference = Safety Benefits
Driver Completely Ejected, Unrestrained	0	20	315	-295
	1	743	1038	-295
	2	905	879	26
	3	641	603	38
	4	58	51	7
	5	133	127	6
	Fatal	727	214	513
	Total	3227	3227	0
	MAIS	Present Injury Distri-bution	Est. Injury Distribution with Ejection Prevented	Difference = Safety Benefits
Passenger Completely Ejected, Unrestrained	0	0	62	-62
	1	557	630	-73
	2	497	478	19
	3	259	241	18
	4	25	22	3
	5	19	15	4
	Fatal	133	42	91
	Total	1490	1490	0
	MAIS	Present Injury Distri-bution	Est. Injury Distribution with Ejection Prevented	Difference = Safety Benefits
Driver Partially Ejected, Restrained	0	0	130	-130
	1	502	550	-48
	2	583	555	28
	3	164	141	23
	4	6	2	4
	5	34	30	4
	Fatal	168	49	119
	Total	1457	1457	0

Table 9.8 (Continued)

	MAIS	Present Injury Distri-bution	Est. Injury Distribution with Ejection Prevented	Difference = Safety Benefits
Driver Partially Ejected, Unrestrained	0	56	327	-271
	1	1755	2006	-251
	2	818	781	37
	3	276	235	41
	4	45	37	8
	5	179	172	7
	Fatal	602	173	429
	Total	3731	3731	0

	MAIS	Present Injury Distri-bution	Est. Injury Distribution with Ejection Prevented	Difference = Safety Benefits
Passenger Partially Ejected, Restrained	0	0	45	-45
	1	183	222	-39
	2	116	117	-1
	3	22	21	1
	4	0	0	0
	5	16	15	1
	Fatal	119	36	83
	Total	456	456	0

	MAIS	Present Injury Distri-bution	Est. Injury Distribution with Ejection Prevented	Difference = Safety Benefits
Passenger Partially Ejected, Unrestrained	0	0	46	-46
	1	188	237	-49
	2	192	185	7
	3	144	136	8
	4	3	2	1
	5	8	7	1
	Fatal	115	37	78
	Total	650	650	0

Table 9.8 (Continued)

	MAIS	Present Injury Distri-bution*	Est. Injury Distribution with Ejection Prevented	Difference = Net Safety Benefits
All Ejection Categories	0	76	925	-849
	1	3928	4683	-755
	2	3111	2995	116
	3	1506	1377	129
	4	137	114	23
	5	389	366	23
	Fatal	1864	551	1313
	Total	11011	11011	0

* The injury distributions for completely ejected drivers and passengers, as reported in Table 8.2, are not included in this table. Those ejected were using shoulder belts only (with two exceptions); such restraints will not be permitted beginning with the 1998 passenger car and 1999 light truck model year fleets. It is assumed that these occupants would wear lap shoulder belts in the future and not be ejected. Ejection prevention would be attributable to restraint usage, not advanced glazing.

The last part of Table 9.8 reports the estimated injury distribution for all ejected occupants before and after the installation of advanced glazing and the difference in these distributions. As reported, the estimated change in the injury distribution would be as follows (note the signs have been changed so the direction of change will be more readily understood when the data are presented alone):

MAIS	Change in Injury Levels
0	+849
1	+755
2	-116
3	-129
4	-23
5	-23
Fatal	-1313
Total	0

In summary, an estimated 1,313 fatalities and 1,297 serious ("A") injuries would be prevented by installing advanced glazing in the front side windows of light vehicles. As estimated, the redistribution of these prevented fatalities and serious injuries would result in the following net safety benefits: A total of 1,313 fewer fatalities, 175 fewer serious (MAIS 3+) injuries, and 116 fewer moderate (MAIS 2) injuries; in addition, 849 presently injured, ejected occupants would be uninjured as the result of their being retained inside their vehicles by advanced glazing. The number of cases in which a minor injury (MAIS 1) was the most severe injury would increase by 849.

10. Cost Effectiveness

This section compares the cost of advanced glazing to the estimated safety benefits. The cost of advanced glazing would be incurred by consumers at the time of vehicle purchase in the form of higher sales prices. On the other hand, the ejection mitigation benefits of advanced glazing would accrue over the operating lives of the vehicles they purchase. The benefits that would be realized would be confined to safety benefits; advanced glazing and other "crashworthiness" technologies do not provide vehicle property damage or other categories of savings associated with crashes being prevented, as do "crashavoidance" technologies, such as advanced brake systems, center high mounted stop lamps, and vehicle modifications that improve driver visibility. Vehicles equipped with advanced glazing would still be heavily damaged in ejection-producing collisions, and property damage loss and the expense associated with congestion, police investigation, and site cleanup would still exist.

To provide an indication of the cost effectiveness of advanced glazing in preventing and mitigating the severity of injuries, a cost per "equivalent" fatality prevented was derived. Such a computation provides a basis for assessing the cost-effectiveness of advanced glazing, as well as providing a meaningful way to assess the merit of various, often competing vehicle modifications.

The approach used to determine how many injuries are "equivalent" to a fatality is based on "willingness to pay". This approach measures individuals' willingness to pay to avoid the risk of death or injury based on societal behavioral measures, such as pay differentials for more risky jobs. The estimates of willingness to pay by MAIS level can be found in "The Economic Cost of Motor Vehicle Crashes", NHTSA, September 1992, DOT HS 807-876 (Note: "Non-injury Components" from Table 1-2, travel delay and property damage, are subtracted from the values in Table B-1 in Appendix B). These values were derived from "The Costs of Highway Crashes," by Ted R. Miller, et al., The Urban Institute, October 1991, for the Federal Highway Administration; the values have been updated here to 1994 price levels. The Miller paper uses the term "rational investment level" for what individuals typically pay for increases in their safety and the costs that the rest of society bears when an individual is killed or injured, including transfer payments.

Table 10.1 presents the estimated rational investment level or comprehensive injury costs for a fatal injury and nonfatal injury by MAIS injury severity level.

Table 10.1
Rational Investment Level to Prevent One Injury
(1994 Dollars)

Severity	Value per Injury
MAIS 1	$ 6,820
MAIS 2	119,740
MAIS 3	445,430
MAIS 4	1,132,110
MAIS 5	2,362,110
Fatal	2,916,400

Table 10.2 presents the calculation of equivalent fatalities that would be saved each year if advanced glazing were installed in front side windows of the light vehicle fleet. These have been calculated by comparing the value of a fatality to the value of each injury level to derive the number of injuries for each injury level that are "equivalent" to one fatality. The net number of injuries that would be prevented for each injury level is divided by the number of injuries that are equivalent to one fatality for the respective injury level to calculate the number of equivalent fatalities that would be prevented. These "equivalent" fatalities are then added to the number of fatalities to estimate the number of fatalities and equivalent fatalities saved. For brevity, the latter estimate is simply stated to be the number of equivalent fatalities saved. As shown, an estimated 1,363 equivalent fatalities would be prevented annually when the light vehicle fleet was fully

equipped with advanced glazing in the front side windows.

Table 10.2
Calculation of "Equivalent" Fatalities Prevented

Safety Benefits - Injuries Prevented		Comprehensive Cost per Injury	No. of Injuries Equivalent to One Fatality*	Estimated No. of Equivalent Fatalities**
MAIS				
1	-755	$ 6,820	427.6	-2
2	116	$ 119,740	24.4	5
3	129	$ 445,430	6.5	20
4	23	$1,132,110	2.6	9
5	23	$2,362,310	1.2	18
Fatal	1313	$2,916,400	1	1313
Total				1,363***

* Calculated by dividing the cost of a fatality ($2,916,400) by the cost of the respective level of injury
** Calculated by dividing the net number of injuries that would be prevented for each injury level by the number of injuries equivalent to one fatality for the respective injury level
*** Comprised of 50 "equivalent" fatalities plus 1313 fatalities

A measure of the cost effectiveness can be computed by dividing the estimated annual consumer cost of advanced glazing by the estimated equivalent fatalities that would be prevented. In addition to being an indicator of the cost effectiveness, this provides a useful way to assess the relative merit of various vehicle modifications, as mentioned above. To obtain a rough estimate of the annual consumer cost of installing advanced glazing in the front side windows of the light vehicle fleet, it was assumed that the costs estimated above specifically for a 1995 Ford Taurus would be the average cost for all light vehicles. Further, it was estimated that annual sales of new cars and light trucks would total 16 million units (9.5 million passenger cars and 6.5 million light trucks; approximate Data Resources projection, "Review of the U.S. Economy, Long-Range Focus," Summer 1995) in the year 1999-2000 timeframe when any requirement for advanced glazing might be implemented. As presented in column 3 of Table 10.3, the estimated annual consumer cost of installing advanced glazing in the front side windows of new light vehicles would range from $768,000,000 to $1,270,000, depending on the type of glazing installed.

As stated above, while the cost of installing advanced glazing would be incurred by consumers at the time of vehicle purchase, the safety benefits would accrue over the operating life of the light vehicle fleet. Therefore, the estimated number of equivalent fatalities that would be prevented was discounted before it was divided into the estimated cost of advanced glazing to calculate the estimated cost per equivalent prevented. The Office of Management and Budget's revised Circular A-94 specifies that a mid-year discount rate of 7 percent be used in benefit-cost analysis of proposed regulations. The derivations of the discount factors are shown for passenger cars and light trucks in addendum Tables 10.A1 and 10.A2, respectively. It was assumed that safety benefits would accrue year-by-year in proportion to the annual mileage accumulated each year by a given model year fleet as it aged. As shown, the respective passenger-car and light-truck discount factors for the 7 percent rate are .7379 and 0.6956, respectively. The weighted average discount factor the two vehicle types is 0.7207 (assuming annual sales of 9.5 million passenger cars and 6.5 million light trucks). The present discounted value of the number of equivalent fatalities that would be prevented annually by advanced glazing in front side windows is estimated to be 982 (1,363 X 0.7207).

The last column of Table 10.3 presents the estimated cost per "equivalent" fatality prevented for the four items of glazing for which costs were estimated. As shown, the estimated cost per "equivalent fatality" prevented ranges from $782,077 to $1,293,360.

Table 10.3
Cost Per "Equivalent" Fatality Prevented for
Alternative Advanced Glazings Installed in Front Side Windows

Type of Advanced Glazing	Estimated Consumer per Vehicle Cost of Advanced Glazing in Front Side Windows	Estimated Annual Consumer Cost of Installing Advanced Glazing in New Light Vehicles*	Discounted Estimated Number of "Equivalent" Fatalities Prevented	Estimated Cost Per "Equivalent" Fatality Prevented
Trilayer Glass	$48.00	$ 768,000,000	982	$ 782,077
Dupont "Sentry Glas"	$50.50	$ 808,000,000	982	$ 822,811

St Gobain Bilayer	$51.34	$ 821,440,000	982	$ 836,497
Rigid Plastic	$79.38	$1,270,080,000	982	$1,293,360

* The estimate is based on light vehicle annual sales of 16 million units in the 1999-2000 timeframe.

For comparison purposes, following are the estimated cost per equivalent fatality prevented for some recent rulemakings.

Rulemaking	Est. Cost Per Equivalent Fatality Prevented
Passenger cars, side impact protection; FMVSS No. 214	$ 470,000 front seat (1989$) $2,940,000 rear seat $ 730,000 front and rear seats
Light trucks, side door beam; FMVSS No. 214	$1,500,000 - $2,500,000 (1989$)
Upper interior head protection; FMVSS No. 201	$ 402,000 - $ 459,000 front section (1993$) $3,121,000 - $3,568,000 rear section $ 687,000 - $ 784,000 front and rear sections
Light trucks, air bags; FMVSS No. 208	$560,000 - $660,000 (1989$)

Table 10.A1
Mid-Year Discount Factors
Passenger Cars

					Weighted PDV Factors*			
Vehicle Age (Years)	VMT	Survival Prob.	Weighted VMT	Percent Total VMT	2%	4%	7%	10%
1	14,535	1.000	14,535	0.1359	0.1346	0.1333	0.1314	0.1296
2	13,924	0.993	13,827	0.1293	0.1255	0.1219	0.1168	0.1121
3	12,846	0.982	12,615	0.1179	0.1122	0.1069	0.0996	0.0929
4	11,378	0.964	10,968	0.1026	0.0957	0.0894	0.0809	0.0735
5	10,749	0.935	10,050	0.0940	0.0860	0.0788	0.0693	0.0612
6	10,119	0.892	9,026	0.0844	0.0757	0.0680	0.0582	0.0500
7	9,490	0.831	7,886	0.0737	0.0648	0.0571	0.0475	0.0397
8	8,860	0.753	6,672	0.0624	0.0538	0.0465	0.0376	0.0305
9	8,231	0.662	5,449	0.0509	0.0431	0.0365	0.0287	0.0227
10	7,601	0.568	4,317	0.0404	0.0334	0.0278	0.0212	0.0163
11	6,972	0.476	3,319	0.0310	0.0252	0.0206	0.0152	0.0114
12	6,343	0.394	2,499	0.0234	0.0186	0.0149	0.0107	0.0078
13	5,713	0.323	1,845	0.0173	0.0135	0.0106	0.0074	0.0052
14	5,084	0.263	1,337	0.0125	0.0096	0.0074	0.0050	0.0035
15	4,454	0.213	949	0.0089	0.0067	0.0050	0.0033	0.0022
16	3,825	0.172	658	0.0062	0.0045	0.0033	0.0022	0.0014
17	3,195	0.139	444	0.0042	0.0030	0.0022	0.0014	0.0009
18	2,566	0.112	287	0.0027	0.0019	0.0014	0.0008	0.0005
19	1,937	0.090	174	0.0016	0.0011	0.0008	0.0005	0.0003
20	1,307	0.073	95	0.0009	0.0006	0.0004	0.0002	0.0001
Total			106,953	1.0000	0.9094	0.8327	0.7379	0.6617

* Calculated by multiplying "Present Total VMT" by the respective discount rate factor for each year as reported in Table 10.A3.

Table 10.A2
Mid-Year Discount Factors
Light Trucks

Vehicle Age (Years)	VMT	Survival Prob.	Weighted VMT	Percent Total VMT	Weighted PDV Factors* 2%	4%	7%	10%
1	14,200	1.000	14,200	0.1108	0.1097	0.1086	0.1071	0.1056
2	14,800	0.999	14,785	0.1153	0.1120	0.1087	0.1042	0.1000
3	13,900	0.988	13,733	0.1071	0.1020	0.0971	0.0905	0.0844
4	12,200	0.966	11,785	0.0919	0.0858	0.0801	0.0725	0.0659
5	11,100	0.946	10,501	0.0819	0.0749	0.0687	0.0604	0.0533
6	9,900	0.925	9,158	0.0714	0.0641	0.0576	0.0492	0.0423
7	9,300	0.897	8,342	0.0651	0.0572	0.0504	0.0419	0.0350
8	8,800	0.862	7,586	0.0592	0.0510	0.0441	0.0356	0.0290
9	8,000	0.825	6,600	0.0515	0.0435	0.0369	0.0290	0.0229
10	7,600	0.771	5,860	0.0457	0.0379	0.0315	0.0240	0.0185
11	7,300	0.710	5,183	0.0404	0.0328	0.0268	0.0199	0.0149
12	6,900	0.645	4,451	0.0347	0.0276	0.0221	0.0159	0.0116
13	6,000	0.573	3,438	0.0268	0.0209	0.0164	0.0115	0.0081
14	6,000	0.502	3,012	0.0235	0.0180	0.0138	0.0094	0.0065
15	5,300	0.441	2,337	0.0182	0.0137	0.0103	0.0068	0.0046
16	5,000	0.380	1,900	0.0148	0.0109	0.0081	0.0052	0.0034
17	5,700	0.320	1,824	0.0142	0.0103	0.0074	0.0047	0.0030
18	5,100	0.260	1,326	0.0103	0.0073	0.0052	0.0032	0.0020
19	4,600	0.200	920	0.0072	0.0050	0.0035	0.0021	0.0012
20	4,200	0.140	588	0.0046	0.0031	0.0021	0.0012	0.0007
21	4,000	0.080	320	0.0025	0.0017	0.0011	0.0006	0.0004
22	3,700	0.050	185	0.0014	0.0009	0.0006	0.0003	0.0002
23	3,200	0.030	96	0.0007	0.0005	0.0003	0.0002	0.0001
24	2,500	0.020	50	0.0004	0.0002	0.0002	0.0001	0.0000
25	2,000	0.010	20	0.0002	0.0001	0.0001	0.0000	0.0000
Total			128,199	1.0000	0.8910	0.8018	0.6956	0.6134

* Calculated by multiplying “Present Total VMT” by the respective discount rate factor for each year as reported in Table 10.A3.

Table 10.A3
Discount Rate Factors

(Mid-year Discount Factors)

Year	2%	4%	7%	10%
1	0.9901	0.9806	0.9667	0.9535
2	0.9707	0.9429	0.9035	0.8668
3	0.6517	0.9066	0.8444	0.7880
4	0.9330	0.8717	0.7891	0.7164
5	0.9147	0.8382	0.7375	0.6512
6	0.8968	0.8060	0.6893	0.5920
7	0.8792	0.7750	0.6442	0.5382
8	0.8620	0.7452	0.6020	0.4893
9	0.8451	0.7165	0.5626	0.4448
10	0.8285	0.6889	0.5258	0.4044
11	0.8123	0.6624	0.4914	0.3676
12	0.7963	0.6370	0.4593	0.3342
13	0.7807	0.6125	0.4292	0.3038
14	0.7654	0.5889	0.4012	0.2762
15	0.7504	0.5663	0.3749	0.2511
16	0.7357	0.5445	0.3504	0.2283
17	0.7213	0.5235	0.3275	0.2075
18	0.7071	0.5034	0.3060	0.1886
19	0.6933	0.4840	0.2860	0.1715
20	0.6797	0.4654	0.2673	0.1559
21	0.6663	0.4475	0.2498	0.7417
22	0.6533	0.4303	0.2335	0.1288
23	0.6405	0.4138	0.2182	0.1171
24	0.6279	0.3978	0.2039	0.1065
25	0.6156	0.3825	0.1906	0.0968

11. SUMMARY AND RECOMMENDATIONS

This report documents the continuing results of our assessment of the safety aspects associated with advanced glazing materials. Based on the safety need, the primary goal evaluated in this project has been the ability to mitigate ejections through front side windows. Computer modeling and NASS accident reports were studied in order to understand how these ejections occur and to determine the opportunities that exist for advanced glazing systems to reduce these ejections. It was also necessary to determine what types of advanced glazing materials were available and if they could be integrated within current vehicle designs. An objective measurement of glazing system performance was developed to evaluate the safety potential and any implications that the advanced glazing systems may have for occupant injuries. Having identified a good potential for ejection mitigation, it was necessary to determine the safety benefits and the anticipated costs of the proposed advanced glazing systems.

This preliminary assessment is very encouraging. There are a variety of glazing materials that could reduce ejections without incurring significant occupant injury. Component tests were designed and conducted to evaluate both the ejection mitigation and the potential for head injury during occupant glazing impacts. The test results for initial designs are quite promising, showing good performance for both occupant retention and injury mitigation. The costs of these glazing systems are much higher than for the tempered glass currently in use. However, the safety benefits are also quite high, which results in a reasonable cost per averted fatality

Specific findings include:

- Retention of a 18 kg (40 lb) impactor at a speed of 24 kmph (15 mph) in a full door impact using all glazing materials.

- For 24 kmph (15 mph) impact speeds, the free motion head impactor measured HIC's from 106 to 540.

- Estimated potential to annually prevent 1,313 fatalities and 1,297 serious injuries.

- Cost to the public between $96.00 and $ 158.76 per 4 door vehicle, with capital investment outlays between 2,652 and 3,072 million dollars.

- Estimated cost per equivalent fatality prevented is between $563,463 and $931,827 dollars.

These research results are considered preliminary. There are some significant aspects that require further research. A partial list of these considerations are listed below;

- Planar Impact Analysis - Due to the mandate for rollover protection research, this project has focused on the full ejections, during rollovers. The accident investigation and computer simulation efforts need to be extended to more fully evaluate the partial ejections that are occurring in planar accidents.

- Testing Repeatability and Reproducibility - The impactor tests have been very encouraging. Further component testing is necessary to evaluate the repeatability and reproducibility of the impact testing. Also, the sensitivity of the impact locations should be evaluated.

- Injury Criteria - It is necessary to establish injury criteria and pass/fail limits for the component testing. Sled tests need to be conducted to establish if there is a relationship between the head injury measured by the impactor and similar measurements made on a dummy. Additionally, the potential for neck injury should be evaluated.

- Full Scale Testing - Simulation, component, and sled test results should be confirmed using full scale vehicle testing, for both planar and rollover accidents. Additional testing should be conducted to evaluated occupant retention from windows that are damaged prior to occupant contact.

- Additional Vehicles - The initial encapsulation design has been conducted for a single older model vehicle. Encapsulation design, frame modifications, and testing should be extended to newer models vehicles with different sizes of side window glazing.

- Extend Benefits Analysis - The safety benefits for occupants ejected through rear windows should be estimated. It is also desired to evaluate the effects of changes in seat belt useage upon the benefits estimates.

The preliminary results from this research project have demonstrated that alternative glazing systems offer a significant safety potential. The research outlined in this report should be continued to more fully evaluate the safety implications of alternative glazing systems. Also, cooperative work with the automotive manufacturers and suppliers has only begun.