U.S. Department
of Transportation

**National Highway
Traffic Safety
Administration**

DOT HS 806 693
NHTSA Technical Report

February 1985

AN EVALUATION OF WINDSHIELD GLAZING AND INSTALLATION METHODS FOR PASSENGER CARS

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT HS-806 693		

4. Title and Subtitle
An Evaluation of Windshield Glazing and Installation Methods for Passenger Cars

5. Report Date
February 1985

6. Performing Organization Code

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8. Performing Organization Report No.

9. Performing Organization Name and Address
Office of Program Evaluation
National Highway Traffic Safety Administration
Washington, D.C. 20590

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
Department of Transportation
National Highway Traffic Safety Administration
Washington, D.C. 20590

13. Type of Report and Period Covered
NHTSA Technical Report

14. Sponsoring Agency Code

15. Supplementary Notes
An agency staff review of two existing Federal regulations performed in response to Executive Order 12291.

16. Abstract
Federal Motor Vehicle Safety Standard 205 sets requirements for the penetration resistance of windshields upon impact while Standard 212 regulates windshield retention in crashes. The High Penetration Resistant (HPR) windshield, developed during the 1960's, was designed to crumple and deform at speeds where earlier windshields would have been penetrated by head impacts. Adhesive bonding provided a tighter windshield installation method than earlier rubber gasket designs. The objectives of this agency staff evaluation are to determine if HPR windshields and adhesive bonding achieved their performance objectives in highway crashes and to measure their casualty-reducing benefits, side effects and costs. The study is based on statistical analyses of National Crash Severity Study, New York, Texas, Multidisciplinary Accident Investigation and Fatal Accident Reporting System data. It was found that:

o HPR glazing doubled the impact velocity needed for the occupant's head to penetrate the windshield, preventing 39,000 serious lacerations and 8,000 facial fractures per year.

o Adhesive bonding halved windshield bond separation and occupant ejection through the windshield portal, saving 105 lives per year.

o HPR glazing did not increase the risk of concussions and adhesive bonding did not increase the injuries of persons who were not ejected.

o HPR glazing added $6 (in 1982 dollars) to the lifetime cost of owning and operating a car, but adhesive bonding saved $15 per car.

17. Key Words
windshield; glazing; windshield mounting; crashworthiness; accident analysis; evaluation; statistical analysis; cost effectiveness; ejection; head injuries

18. Distribution Statement
Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	278	

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LIST OF ABBREVIATIONS

ACIR	Automotive Crash Injury Research
AIS	Abbreviated Injury Scale
AMC	American Motors Corporation
ANSI	American National Standards Institute
df	degrees of freedom
FARS	Fatal Accident Reporting System
GM	General Motors
HPR	High Penetration Resistant
MDAI	Multidisciplinary Accident Investigation
mph	miles per hour
MY	Model Year
NAGS	National Auto Glass Specifications, Inc.
NCSS	National Crash Severity Study
NHTSA	National Highway Traffic Safety Administration
NYSICS	New York State Injury Coding System
PPG	Pittsburgh Plate Glass Industries
psi	pounds per square inch
SAE	Society of Automotive Engineers
SAS	Statistical Analysis System
TAD	Traffic Accident Data project accident severity scale
VIN	Vehicle Identification Number
VW	Volkswagen

ACKNOWLEDGMENTS

I am grateful to Mike Pometto of the Silver Spring Glass Company (Silver Spring, Maryland), a car enthusiast, who shared with me his files on windshield installation specifications for cars dating back to model year 1932. Bob Gardner (NHTSA), Ernie Grush (Ford), Dietmar Haenchen (Volkswagen), Vic Herliczek (Libby-Owens-Ford), C. M. Kennedy (Chrysler), Bob Krauss (NHTSA), Carl McConnell (MVMA), Mike McKale (GM), Kermit Morgan (AMC) and Larry Patrick (consulting engineer) also provided information on windshield glazing and installation methods.

Carl Clark, Ed Jettner and Steve Oesch reviewed the manuscript and suggested some additional analyses. Bob Blodgett and Jerome Kossar also helped me with data sources and suggestions for analyses.

Alleyne Monkman typed the report.

SUMMARY

Since 1960, there have been major changes in the design of windshields for passenger cars and in the techniques whereby windshields are installed in cars.

In 1965, the domestic manufacturers installed High Penetration Resistant (HPR) windshields, on an experimental basis, in a few models and in 1966, HPR became standard equipment in all domestic cars. Before HPR, the plastic interlayer of safety glazing used in windshields was easily torn by broken glass, permitting the occupant's head to tear through and penetrate the windshield in low-speed crashes. Windshield penetration was believed to be the cause of most of the disfiguring or disabling head injuries associated with windshield contact. Rodloff, Patrick, Rieser and other researchers found techniques to obtain a looser glass-plastic bond in safety glazing, allowing the glass to crumple away rather than tear the plastic. The new manufacturing techniques, in combination with a thicker plastic layer, became known as the "HPR windshield," which was found to double the speed needed for the windshield to be penetrated in laboratory impact tests. Federal Motor Vehicle Safety Standard 205, which took effect on January 1, 1968, incorporated American National Standards Institute's safety codes which the motor vehicle industry had already imposed upon themselves to assure that all motor vehicles have windshields as penetration-resistant as HPR.

Before 1963, windshields were installed in a car by means of a rubber gasket. In 1963, butyl tape was used to adhesively bond the windshield to the frame on a small test fleet of General Motors cars. Adhesive bonding became standard on a few GM models in 1964. The domestic manufacturers gradually shifted from rubber gaskets to adhesive bonding (initially butyl tape and later, in some cases, polyurethane sealant) after 1964, but rubber gaskets remained on some domestic models until 1978. The objectives of adhesive bonding were not explicitly stated, but two may be inferred: to provide a tighter bond between windshield and car, preventing the windshield from becoming dislodged in a crash, denying occupants an avenue for ejection through the gap between windshield and frame; to reduce manufacturing cost by eliminating the rubber gasket. On January 1, 1970, in the middle of the transition from rubber gaskets to adhesive bonding, Federal Motor Vehicle Safety Standard 212 took effect for passenger cars. Standard 212 limits the amount of windshield bond separation allowed in a 30 mph barrier crash and has the explicit objective of preventing occupant ejection through the windshield portal. But the relationship of Standard 212 to adhesive bonding is not clear, since, as stated above, rubber gaskets continued to be used in some models well after 1970. It is possible that a 1976 modification in the temperature range for Standard 212 testing may also have accelerated the shift to adhesive bonding.

Foreign cars, as a matter of fact, continued to use mostly rubber gaskets throughout the 1970's. But Volkswagen, which had virtually a "pop-out" windshield before 1970, did install clips between the gasket and the frame in response to Standard 212. It is possible that other German manufacturers also implemented similar devices at about that time.

Executive Order 12291 (February 1981) requires agencies to evaluate their existing major regulations, including any rule whose annual effect on the economy is $100 million or more. The objectives of an evaluation are to determine the actual benefits--lives saved, injuries prevented, damage avoided--and costs of safety equipment installed in production vehicles in connection with a standard and to assess cost-effectiveness.

This report is an evaluation of HPR windshields for passenger cars, adhesive bonding of the windshields of domestic cars and the changes in the installation of Volkswagen and other German windshields made in response to Standard 212. (HPR glazing and adhesive bonding were also implemented in vehicles other than passenger cars, but that will be evaluated at a later date.)

The report does not evaluate the effects of the shift from laminated to tempered side windows which took place in about 1960--there were far too few cases on NHTSA accident files of occupants who were injured by contact with side windows in cars of the 1960 era. It also does not evaluate glass-plastic glazing concepts such as Securiflex because they have not yet (October 1984) been implemented in large numbers on cars sold in the United States. NHTSA evaluations of existing safety devices, as stated above, are based on the actual operating experience of production vehicles: something not yet available in sufficient quantity for glass-plastic glazing. It should be noted however, that laboratory tests show that glass-plastic glazing may have great potential for reducing minor facial lacerations (a great many of which still remain, even after HPR) and occupant ejection through side windows. If the concept is implemented on a large number of production vehicles, NHTSA will certainly evaluate their on-the-road experience.

HPR windshields have already been informally evaluated. The dramatic reduction in the demand for facial plastic surgery following the introduction of HPR made it clear to the safety community that HPR has been, perhaps, more successful than any other standard. The effectiveness of HPR has been shown in a number of laboratory studies and statistical accident analyses. It remains for this evaluation to give specific estimates of the numbers and types of injuries prevented by HPR, to compare laboratory and highway accident performance, and to investigate the possibility of negative side effects such as blunt impact trauma or secondary benefits such as a reduction of minor injuries.

Windshield installation methods, by contrast, have been a controversial subject since the mid-1960's. On the one hand, no study to date appears to have shown whether or not tighter bonding methods achieved Standard 212's goal of reducing occupant ejection. On the other hand, studies by Fargo (accident analysis of pre-HPR cars) and Rodloff and Breitenbuerger (drop tests with HPR glazing) warn that tight bonding has serious negative side effects for persons who are not ejected: lacerations, blunt impact trauma and a reduced windshield penetration velocity. But Patrick's and Trosien's sled tests with dummies found little or no side effect. Who is right? Thus, the evaluation must analyze the effect of installation method on ejection and on persons who are not ejected. Both analyses must be performed separately for domestic cars (effect of adhesive bonding) and German cars (effect of Standard 212); the analysis of persons who are not ejected, separately for pre-HPR and post-HPR cars.

The strategy of this evaluation was to perform parallel statistical "injury" and "engineering" analyses of accident data. In the case of HPR, the "injury" analysis of the reduction of various types of head trauma was paralleled by an "engineering" analysis of the velocities at which heads penetrate windshields in highway accidents. The objectives were to give an engineering explanation of why injuries were reduced and to compare hardware performance in accidents to the laboratory. In the study of the effect of windshield installation method on ejection, the "injury" analysis of occupant ejection rates was accompanied by an "engineering" analysis of windshield retention in crashes. The analysis of the side effects of windshield installation method on occupants who were not ejected again compared types of head injuries and penetration velocities.

The "engineering" analyses were based on National Crash Severity Study (NCSS) data. The "injury" analyses, in each case, were based on at least 3 files: effect of HPR on injury rates--NCSS, New York State, Texas and Fatal Accident Reporting System (FARS); effect of installation method on ejection--NCSS, Multidisciplinary Accident Investigation (MDAI) and FARS; effect of installation method on injury rates--New York State, NCSS and Texas. New York data were especially useful because they identified the body region and type of injury over a large sample of accidents. When large data files were used (FARS, New York, Texas), the analysis of German cars was limited to Volkswagen, where it is relatively clear that clips were installed very close to the beginning of the 1970 model year. For the smaller data files (NCSS, MDAI), the other German makes are included to increase the available sample size, even though it is not as well known when and if similar modifications were made. Thus, throughout the report, results on "German cars" are the ones based on NCSS and/or MDAI; those on "Volkswagen" are based on the other files. Practically speaking, though, the distinction is of minor importance since Volkswagen accounted for over 85 percent of the German cars sold here during 1965-74.

The cost of the vehicle modifications was estimated by analyzing the components of vehicles produced before and after the modification.

The most important conclusions of this evaluation are that HPR glazing dramatically reduced the number and severity of facial lacerations and fractures while doubling the impact velocity needed to penetrate the windshield in crashes. Adhesive bonding saved lives because it halved windshield separation in crashes and occupant ejection through the windshield portal; the clips installed in the rubber gaskets of Volkswagens in response to Standard 212 had the same effect. In cars with HPR windshields, the installation method had little or no side effect on the injuries of persons who were not ejected. Because each of these conclusions is supported by analyses of multiple data files, which are remarkably consistent with one another and with the "engineering" analyses, they may be stated confidently.

In two areas, conclusions are drawn less firmly. One concerns the proportion of ejectees through the windshield portal who were killed by injuries sustained while they were still inside the passenger compartment. This proportion is estimated with reasonable precision from NCSS and MDAI data. It is then assumed to equal the proportion of persons, saved from ejection by adhesive bonding, who would have died anyway from interior contacts. The FARS data, unfortunately, were unsuited for an independent verification of this plausable assumption. Thus, in this case, "evidence from multiple data files" is lacking. The other area is the effect of adhesive bonding on injury risk in cars with pre-HPR windshields. New York data show significant negative effects but NCSS and Texas data show none. Thus, while the evaluation clearly shows no side effects with today's windshields, it is unable to resolve the controversy about adhesive bonding in cars with pre-HPR windshields--fortunately, the question has become moot because so few of them remain on the road.

The principal findings and conclusions of the study are the following:

Principal Findings

Effect of HPR glazing on windshield penetration by occupants

- When an occupant's head strikes a safety-glass windshield and tears and penetrates the plastic interlayer, the risk of serious lacerations or fractures to the face, scalp, eyes, nose or mouth is 3 times greater than when the impact merely breaks the glass but leaves the plastic layer intact.

- HPR glazing reduced the likelihood of an occupant penetrating the windshield in frontal crashes by 78 percent, relative to pre-HPR glazing.

o With pre-HPR glazing, there was a 50 percent probability that an unbelted occupant would penetrate the windshield in a frontal crash with a Delta V of 14 miles per hour. With HPR glazing, the likelihood of penetration does not reach 50 percent until Delta V is 31 miles per hour.

Injury-reducing effectiveness of HPR

o The reduction of serious head injuries involving windshield contact, by injury type, was:

	Reduction for HPR (%)	
	Best Estimate	Confidence Bounds
AIS 2-4 lacerations	74	65 to 83
AIS 2-4 eye, nose or mouth injuries	72	58 to 86
AIS 2-4 fractures	56	27 to 85

Those are the types of injuries most characteristically associated with penetration of the windshield.

o HPR glazing also reduced minor lacerations due to contacting the windshield by 25 percent (confidence bounds: 5 to 45 percent).

o HPR windshields had little or no observed effect on injuries characteristic of blunt impact trauma: concussions, contusions and complaints of pain.

o Fatality risk in crashes was not significantly changed by HPR.

<u>Effect of windshield installation method on windshield retention in crashes</u>

o All American manufacturers shifted from installing windshields with a rubber gasket to an adhesive bonding process at some time between 1963 and 1979, depending on the car's make and model. That resulted in an immediate 35 percent reduction and a long-term 50 percent reduction in the proportion of the windshield that became separated from the frame in a frontal crash. The long-term reduction is greater because some of the adhesive bondings initially used by General Motors were looser than their later practice.

o Volkswagen (and, possibly, other German manufacturers) responded to Standard 212 by clipping their rubber gasket to the frame, rather than shifting to adhesive bonding. The clips reduced windshield separation by 51 percent. Nevertheless, the statistics on windshield separation in accidents suggest that post-Standard 212 windshield installations in Volkswagens were looser than pre-Standard 212 rubber gaskets in American cars.

o In a frontal crash with a Delta V of 30 miles per hour, the average amount of windshield separation, by installation method, was:

	Separation (%)
American cars - rubber gaskets	22
American cars - adhesive bonding	15
German cars - pre-Standard 212 gaskets	59
German cars - post-Standard 212 gaskets	39

Standard 212 allows 25 percent bond separation in a staged 30 mph barrier impact.

o Polyurethane sealant and butyl tape--two alternative adhesive bonding methods--provided about the same windshield retention in crashes, for cars of the 1970's.

Effect of windshield installation method on occupant ejection

o In American cars whose windshields were installed by rubber gaskets, 15 percent of the occupant ejections (complete or partial) took place through the windshield portal; in pre-Standard 212 Volkswagens, 17 percent. (Persons who merely penetrate the windshield's plastic interlayer with part of their heads are not normally coded as "partially ejected" by NHTSA accident investigators.)

o Adhesive bonding reduced the risk of ejection through the windshield portal by 50 percent in American cars (confidence bounds: 34 to 66 percent). The clips installed in Volkswagens in response to Standard 212 had the same effect. Reductions of complete and partial ejection were similar.

o On the other hand, only 30 percent of the persons who were ejected through the windshield portal received their most serious injuries as a consequence of the ejection--i.e., from objects exterior to the passenger compartment. As a result, adhesive bonding saves 15 percent (50% of 30%) of the deaths and serious injuries of windshield ejectees (confidence bounds: 7 to 22 percent). Standard 212 had the same effect in Volkswagens.

Effect of windshield installation method on windshield penetration by occupants

o There was no evidence that tighter bonding increased the risk of an occupant penetrating the windshield. In fact, the following nonsignificant reductions were observed:

Adhesive bonding vs. rubber gasket in American cars:	1 percent
Adhesive bonding vs. rubber gasket in American pre-HPR cars:	7 percent
Post-Standard 212 gasket vs. pre-Standard in German HPR cars:	19 percent

Effect of windshield installation method on the injuries of persons who are not ejected

o In American cars with HPR windshields, the installation method (rubber gaskets or adhesive bonding) had little or no effect on the likelihood of any type of head injury.

o In Volkswagens with HPR windshields, Standard 212 likewise had little or no effect.

o In American cars with pre-HPR windshields, the following statistically significant increases of head injury risk were associated with adhesive bonding in New York State data:

	Increase for Adhesive Bonding (%) (Cars with Pre-HPR Windshields)
"Severe bleeding" (i.e., nonminor lacerations)	20
Concussions	50
Contusions and complaints of pain	20

The Texas data do not show any increase, however, in overall injury rates.

Cost of HPR glazing

o The incremental costs per car (in 1982 dollars) for HPR glazing, relative to pre-HPR, based on analyses of vehicle components, are the following:

Initial purchase price increase	$4.45
Lifetime fuel consumption due to 1.05 pound weight increase	1.05
TOTAL COST PER CAR	$5.50

o The annual cost of HPR glazing in the United States (based on 10 million cars sold) is $55 million.

Cost savings due to adhesive bonding

o Adhesive bonding was a less costly way to install a windshield than rubber gaskets. The cost savings per car (in 1982 dollars), based on analyses of vehicle components, are the following:

Initial purchase price reduction	$11.50
Lifetime fuel savings due to 3.98 pound weight reduction	3.98
TOTAL SAVINGS PER CAR	$15.48

o The annual savings due to adhesive bonding in the United States (based on 7.5 million domestic cars sold) is $116 million.

Annual benefits of HPR glazing

o The annual benefits, when all cars in the United States have HPR glazing, will be:

Reduction of Head Injuries with	Best Estimate	Confidence Bounds
AIS 2-4 laceration or avulsion	39,000	25,000 - 53,000
AIS 2-4 fracture	8,000	1,000 - 18,000
AIS 2-4 (any type)	47,000	31,000 - 62,000
AIS 2-4 eye, nose or mouth injury	19,000	9,700 - 29,000
AIS 1 laceration	142,000	22,000 - 315,000

Annual benefits of adhesively bonded windshields in American cars

o When all domestic cars in the United States will have windshields installed by adhesive bonding, it will save 105 lives per year (confidence bounds: 35 to 175) and 160 nonfatal AIS 3-5 (serious) casualties.

Annual benefits of Standard 212 for Volkswagens

o When all Volkswagens registered in the United States meet Standard 212, it will save 7 lives and 11 AIS 3-5 casualties per year.

Cost-effectiveness

o Since HPR windshields save 47,000 AIS 2-4 injuries and cost $55 million, they eliminate 850 AIS 2-4 injuries per million dollars of cost (confidence bounds: 560 to 1130).

o Adhesive bonding saves lives while reducing the cost of a car.

Conclusions

HPR Windshields

o HPR glazing greatly reduced the risk of serious lacerations of the face, scalp and mouth, fractures of the facial bones and nose and occular avulsions.

o The HPR windshield achieved its objective of steeply increasing the impact velocity needed for an occupant's head to tear and penetrate through the windshield's plastic interlayer. That explains HPR's success in mitigating the types of serious injuries listed above, because all of them are characteristically associated with penetrated windshields.

o The penetration velocities of windshields, both HPR and pre-HPR, in highway accidents were almost identical to those observed in laboratory tests. In short, HPR fully delivered in real crashes what it promised in the laboratory.

o Also, as predicted from laboratory testing, HPR had no negative side effects, such as increasing the risk of injuries associated with blunt impact trauma (concussions, contusions and complaints of pain). It had little or no effect on fatalities.

o The accident data indicate that HPR has also reduced minor lacerations significantly. Those injuries are typically associated with windshields that are cracked but not penetrated. Their reduction confirms heretofore anecdotal evidence that the HPR interlayer, in addition to resisting penetration, causes glass to crack into smaller, less injurious pieces. Nevertheless, the majority of minor lacerations still remains even after HPR.

o About half of the much smaller number of serious injuries which still occur after HPR are concussions--blunt impact trauma. The other half are lacerations and fractures: two-thirds of them did not involve windshield penetration and only the remaining third occurred at speeds too high for HPR to prevent penetration. In other words, what was once the most characteristic windshield-related serious injury has been largely eliminated.

o HPR glazing is a highly cost-effective safety device. HPR eliminated about 80 percent of penetration-related serious lacerations. No other safety device evaluated by NHTSA to date (October 1984) has come that close to eliminating the injury mechanism it was targeted to mitigate.

Windshield installation methods

o The risk of (complete or partial) occupant ejection through the windshield portal was significantly reduced when domestic manufacturers began to install windshields by adhesive bonding rather than rubber gaskets. A similar reduction was accomplished when Volkswagen began to clip its rubber gaskets to the car's windshield frame, in response to Standard 212.

o Unlike the situation that prevails with other ejection portals, the majority of persons ejected through the windshield portal received their most serious injuries before they left the passenger compartment--and would still have received them even if their ejection had been prevented. This attenuates the life-saving potential of tighter windshield installation methods; nevertheless adhesive bonding and Volkswagen's clipping of the gasket significantly reduced fatalities and serious injuries.

o Virtually all ejections through the windshield portal occur after the windshield has been partially or completely dislodged from its frame. Adhesive bonding and Volkswagen's clipping prevented ejection because they reduced the amount of windshield separation from the frame--in fact, the reductions in ejection and bond separation were nearly identical.

o Butyl tape and polyurethane sealant--two alternative adhesive bonding techniques--provide approximately equal windshield retention in crashes.

o The types of rubber gasket installations found in American cars could have or did pass Standard 212. The domestic manufacturer's shift from rubber gaskets to adhesive bonding was not necessitated by Standard 212 but was prompted by other factors, such as additional safety or cost savings. By contrast, the rubber gaskets of pre-Standard 212 Volkswagens were much closer to a "pop-out" design; the gaskets were clipped to the frame at the time that Standard 212 took effect. Even the post-standard Volkswagen windshields were more loosely installed than those of pre-standard American cars.

o In cars with HPR windshields, the shift to adhesive bonding clearly did not have any negative side effects such as reducing windshield penetration velocity or increasing the risk of any type of injury to occupants who are not ejected. Neither did the shift to clipped rubber gaskets in Volkswagens.

o The accident data strongly confirm Patrick's and Trosien's sled tests with dummies and full windshield assemblies, which also showed no side effects. They do not support Rodloff and Breitenbuerger's drop tests of headforms onto less-than-fullsize glazing samples, which showed that tight bonding defeated a substantial proportion of HPR's gain in penetration velocity. It must be concluded that the drop tests simulated the interaction of the windshield and the frame in crashes less realistically than the sled tests.

o The accident data of this report show that Fargo's analysis of ACIR accident data, which was based on pre-HPR windshields and found significant negative side effects for adhesive bonding, cannot be carried over to HPR windshields.

o In cars with pre-HPR windshields, one of the accident files analyzed in this report associated significant increases in lacerations, concussions and minor blunt-impact trauma with adhesive bonding, supporting Fargo's results. But analyses of two other accident files did not confirm that association. The question of whether adhesive bonding had negative side effects in pre-HPR cars remains unresolved; it has, however, become moot because few pre-1966 cars remain on the road.

o The shift from rubber gaskets to adhesive bonding reduced the cost of purchasing and operating a car.

o Since adhesive bonding (in cars with HPR windshields) provided significant benefits without negative side effects while reducing cost, it is certainly a cost-effective safety improvement.

CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1 Evaluation of Federal Motor Vehicle Safety Standards

Executive Order 12291, dated February 17, 1981, requires Federal agencies to perform evaluations of their existing regulations, including those rules which result in an annual effect on the economy of $100 million or more [10]. The evaluation shall determine the actual costs and actual benefits of the existing rule.

The National Highway Traffic Safety Administration began to evaluate its existing Federal Motor Vehicle Safety Standards in 1975. Its goals have been to monitor the actual benefits and costs of safety equipment installed in production vehicles in response to standards and, more generally, to assess whether a standard has met the specifications of the National Traffic and Motor Vehicle Safety Act of 1966 [36]: practicability, meet the need for motor vehicle safety, protect against "unreasonable" risk of accidents, deaths or injuries, provide objective criteria. The agency has published 8 comprehensive evaluations to date.

1.2 Evaluation of Standards 205 and 212

Federal Motor Vehicle Safety Standard 205 specifies requirements for glazing materials for use in motor vehicles and motor vehicle equipment. It took effect on January 1, 1968 [5]. The standard, however, primarily incorporates the United States of America Standards Institute's (now known as ANSI) Safety Code Z26.1 dated July 15, 1966 [45]. The 1966 version of Safety Code Z26.1 differs from the 1950 version (which contains a number of strength, durability and transparency tests for all types of automotive glass) in that it also incorporates SAE Standard J938, "Drop Test for Evaluating Laminated Safety Glass for Use in Automotive Windshields," dated October 1965 and developed under the auspices of the SAE Glazing Committee [37]. The drop test, which applies only to the windshield, specifies that a 5-pound steel ball dropped from a 12-foot height must not penetrate a sample of windshield glazing on more than 2 out of 10 tests. The SAE standard coincided with the introduction of High Penetration Resistant (HPR) windshields in all domestic passenger cars in model year 1966. The 12 foot drop height allows the ball to be accelerated to approximately 19 miles per hour--too slow to break through HPR glazing but enough to penetrate pre-1966 windshields (see Section 2.1). Other automotive glass components--side windows, backlight--were not as significantly affected, generally having been constructed of tempered glass since 1960. In other words, Standard 205 is based largely on earlier SAE and ANSI standards; the installation of HPR windshields was the primary vehicle modification associated with those standards.

The purpose of Standard 205 "is to reduce injuries resulting from impact to glazing surfaces, to ensure a necessary degree of transparency and to minimize the possibility of occupants being thrown through the vehicle windows in collisions." The "standard applies to glazing materials for use in passenger cars, multipurpose passenger vehicles, trucks, buses, motorcycles, slide-in campers and pickup covers designed to carry persons while in motion [5]."

Standard 212 establishes windshield retention requirements for motor vehicles during crashes [6]. It took effect on January 1, 1970, for passenger cars and on September 1, 1978, for most light trucks, vans and multipurpose vehicles. The standard requires that not less than 75 percent of a vehicle's windshield periphery remain bonded to the frame after a 30 mph frontal barrier crash test (or 50 percent of the periphery if a car is equipped with passive restraints).

The vehicle modification in domestic passenger cars that would appear most closely related to Standard 212 has been the gradual shift from mounting windshields within a rubber gasket to attaching them directly to the frame with an adhesive substance. The shift took place in domestic cars during 1963-78. Obviously, the shift was not absolutely necessary to meet the standard: rubber gaskets continued to be used in some makes and models until 1978, 8 years after the standard's effective date. Other factors, such as the lower cost of adhesive bonding or development of improved adhesives may also have influenced the phasing out of rubber gaskets.

An additional conjecture concerning the eventual demise of rubber gaskets during the late 1970's may be found in the Federal Register notice of August 30, 1976 (41 FR 36493) in which the tests for Standard 212 were modified to include a temperature range from 15 to 110 degrees Fahrenheit. This change was made because it was found that the retention capability of windshield moldings varies significantly with temperature of the mounting material. After the change, manufacturers may have selected a form of chemical bonding which is relatively insensitive to temperature.

But Volkswagen (and possibly other German manufacturers) did not shift from rubber gaskets to adhesive bonding. Instead, they clipped the windshield to the metal frame in response to Standard 212 [14].

The stated purpose of Standard 212 "is to reduce crash injuries and fatalities by providing for retention of the vehicle windshield during a crash, thereby utilizing fully the penetration-resistance and injury-avoidance properties of the windshield glazing material and preventing the ejection of occupants from the vehicle [6]." Above all, the objective is to prevent occupant ejection through the portal that is opened if the windshield were to become separated from the vehicle.

Why evaluate Standards 205 and 212? More specifically, why evaluate the HPR windshield, adhesive bonding and Volkswagen's clipped rubber gaskets, the three major vehicle modifications associated with the standards? First, because the windshield is an extremely important source of occupant injuries; the pre-HPR windshield may have ranked first or second among vehicle components as a source of moderate-to-severe injuries [2], [35]. Many of the injuries left victims permanently disfigured. Second, only one comprehensive statistical analysis of windshield modifications has been published--by R. B. Fargo in 1968 [9]--and some of its findings were controversial. Many new accident data files have become available since then. As for the HPR windshield, while case-by-case accident analysis and laboratory testing has clearly shown it to be effective, its actual benefits and limitations have not been adequately quantified. Much less is known about windshield bonding. There is no accident analysis which shows that tighter bonding achieved its primary objective of reducing ejection. Fargo's accident data indicated that adhesive bonding had a side effect of substantially increasing the injury risk of occupants of cars with pre-HPR windshields who were not ejected--an alarming conclusion that was supported by European engineers, disputed by Americans and never adequately tested with later accident data on cars with HPR windshields.

1.3 Windshield injury mechanisms

Windows of ordinary plate glass have little ability to absorb impact energy. They easily shatter into large sharp-edged or jagged pieces that can severely lacerate the skin of a person striking them. Since 1927, domestic manufacturers have used laminated safety glass for windshields [9], p. 2. The windshield consists of a thin layer of plastic sandwiched between two layers of plate or, later, float glass. Upon impact, the glass layers break into numerous small pieces which are supposed to adhere to the plastic and not expose sharp or jagged edges to the impacting occupant. The plastic layer, unlike the glass, is deformable and can absorb some energy and resist penetration by the occupant's head.

Unfortunately, the pre-HPR safety glass did not perform as desired except in low speed impacts. The glass and plastic layers were too rigidly attached to one another. As a result, when the glass broke on impact, it often tore the plastic sheet at the points of breakage exposing long, sharp glass edges. The plastic layer was also too thin to absorb much energy and, aggravated by the tendency of the glass to tear the plastic, rather easily allowed penetration of the windshield by the impacting occupant.

"Nonminor" facial and scalp lacerations are characteristic of pre-HPR windshields and typically result from contacting exposed glass edges. Lacerations are far more common on the head or face than on other body regions because the occupant's head is more likely than other body parts to strike the windshield in a frontal collision. Front-seat passengers are more vulnerable than drivers because the steering assembly sometimes prevents drivers from contacting the windshield. In various editions of the Abbreviated Injury Scale (AIS), "nonminor" lacerations--those with AIS = 2--have been defined as those which cause disfigurement [49], extend into the subcutaneous tissue [1], or require more than first aid or simple closure [1]. In the Restraint Systems Evaluation Project, lacerations over 3 inches long were apparently also coded AIS 2 [7]. A laceration involving major nerves or blood vessels is coded AIS 3 (severe-nondangerous). If the HPR windshield had not been installed in passenger cars, there would be approximately 53,000 AIS 2-3 lacerations each year. They accounted for over 10 percent of all passenger car occupant injuries in that severity range.

Another injury pattern characteristic of pre-HPR windshields occurs when the head partially penetrates the windshield and rebounds toward the car interior. On the rebound, the sharp, jagged perimeter of the hole in the windshield can gouge into the occupant's eyes, mouth or nose, resulting in occular avulsion (AIS 2-3), deep lacerations of the lips or tongue (AIS 2), or compound, displaced or open nasal fractures (AIS 2). Without the HPR windshield, there would be 26,000 of these each year.

The edges of a broken windshield can exert enough concentrated force to fracture some of the relative delicate facial bones or even the skull [41]. Without the HPR windshield, there would be 14,000 of these AIS 2-3 injuries each year.

When impact speeds are lower and the windshield cracks without breaking or tearing the plastic layer, minor lacerations or abrasions (AIS 1) can occur from small slivers of glass that break off the windshield or from the cracks in the windshield surface. About 569,000 of them occur annually.

Blunt impacts of the occupant's head with an unbroken windshield can cause minor injuries such as contusions, headaches and soreness (362,000 per year).

At higher force levels, more serious blunt trauma such as concussions or skull fractures may occur. But windshields--both pre-and post-HPR--are usually broken before force builds up to quite dangerous levels (i.e., Head Injury Criterion of 1000 or more). For occupants of average vulnerability to injury, it is rare even for force to build up to a level sufficient to produce a concussion (see Section 2.1). As a result, there are only 21,000 concussions per year and most of them are at the least severe (AIS 2) level.

Neck injury may occur when the head contacts the windshield. If the torso is still moving forward at that time, the head is displaced rearward relative to the torso, possibly hyperextending the neck, resulting in a whiplash injury not unlike what typically happens in rear impacts. About 76,000 necks are injured annually in conjunction with heads contacting the windshield. Of course, it is unknown how many of those whiplash-type injuries are "caused" by the head contact with the windshield. All but 1,600 of the whiplashes are minor (AIS 1).

Occupants can be wholly or partially ejected through the windshield portal and, subsequently, be seriously injured by objects outside the passenger compartment. Ejection can happen three ways. All of them are rare, but the most common is for the windshield to become partially or completely separated from the frame as a result of severe exterior damage to the vehicle which distorts the frame. The occupant is ejected through the open space where the windshield had been, possibly increasing the gap by his own impact. Less frequently, the occupant's impact alone may dislodge the windshield from the frame. Very rarely, the occupant's impact may break a hole in the windshield large enough to be ejected through even though the bonding to the frame is intact [27]. About 700 persons would be ejected through the windshield and killed each year if adhesive bonding had not been implemented in domestic cars and 50 would be ejected and killed in Volkswagens if their rubber gaskets had not been clipped in response to Standard 212. (Throughout this report, following the practice of NHTSA accident investigators, "partial ejection" does not include cases of persons who merely penetrated the plastic interlayer of the windshield with part of their heads. A partial ejectee's body has to come to rest outside the vehicle, to a large extent, or has to have made contact with external objects during the collision.)

Fatal injuries due to contact with the windshield (no ejection) are rare because, as noted above, the windshield glass usually breaks at a nondangerous force level. Huelke and Gikas' in-depth investigations of 177 occupant fatalities of the pre-HPR era only attributed 2 fatalities to windshield contact [16]. In NCSS, investigators found 16 persons with fatal windshield contact among the 943 occupant fatalities. In Dr. Huelke's opinion, many of the fatal or serious injuries "attributed" to windshields on less-than-in-depth files such as NCSS are misclassified because the windshield damage is obvious while the actual fatal contact with surrounding structures (header, A-pillar) is much more difficult to detect [16]. Similarly, Hermann and Garrett reported that all six fatal head injuries attributed to windshield contact by their investigators were actually found, upon further examination, to have involved simultaneous contact with the header, instrument panel or other structures [15]. It would appear that at most 1 percent of fatalities, or 250 deaths per year, can be attributed to windshield contacts of occupants who are not ejected.

The estimates of the numbers of injuries shown here are derived in Sections 7.2 and 7.3.

1.4 High Penetration Resistant windshields

Before model year 1966, the standard windshield for domestic passenger cars consisted of an 0.015 inch polyvinyl butyral interlayer between two 0.125 inch layers of plate glass. The bond between plastic and glass was too rigid, causing broken glass to tear the plastic. Dummy heads penetrated the windshield in 13 mph impact tests [41].

In the early 1960's, G. Rodloff discovered in Germany that a looser bond between the plastic and glass layers could be obtained by increasing the moisture content of the polyvinyl butyral [43]. This set the stage for the development of improved windshields. "The lower adhesion of the glass to interlayer permits the interlayer to flex away from the glass pane rather than to shear at glass pane fracture [9]." It permits the plastic to bulge upon impact and absorb energy. An undesirable property of moisture levels over 1 percent, however, was that windshields became cloudy with age [42].

American corporations experimented with adhesion properties and moisture levels of polyvinyl butyral and found 0.5-0.6 percent moisture optimal in that it provides a loose bond with the glass while maintaining windshield transparency. Monsanto and DuPont produced polyvinyl butyral with loose adhesion properties and moisture content controlled at that level. The new plastic was called "High Penetration Resistant (HPR) interlayer [52]."

Next, Pittsburgh Plate Glass Industries [42] and the Ford Motor Company [41] produced experimental windshields, varying the thickness of the plastic and glass layers. They felt that an 0.03 inch HPR interlayer between 0.125 plate glass layers provided the best combination: penetration resistance up to 22-29 miles per hour, which was double the speed for existing windshields; blunt impact forces on dummy heads were well below dangerous levels during laboratory tests. (The experiments are described in more detail in Section 2.1.)

This combination became known as the "HPR windshield." It was installed in all domestic passenger cars in model year 1966 and in the Ford Thunderbird in 1965 [13]. It has remained basically unchanged since then, although there have been minor variations in the thickness of the glass layers, with a tendency toward thinner glass (.105 - .115 inches) in downsized, post-1976 cars.

What are the potential benefits and limitations of HPR windshields? Since they bulge rather than tear, occupants will be less exposed to long, sharp glass edges, which should result in a significant reduction of AIS 2-3 lacerations and facial fractures. Eye, nose and mouth injuries due to partial penetration and subsequent retraction of the head should also be reduced. Of course, complete elimination of these injuries cannot be expected because the windshield can still be penetrated at high speeds (Delta V above 25-30 mph) or even at moderate speeds on very hot or cold days [48].

It is uncertain if HPR windshields would have an effect on concussions. A reduction of occupant exposures to long glass edges might alleviate concussions; but the improvement in penetration resistance could increase blunt impact loads on the head--hopefully not too much, though, because the HPR windshield is designed to bulge before a dangerous force level is reached. It is not evident that minor lacerations and abrasions would decrease, because they mostly result from windshield contacts with glass breakage but no penetration of the interlayer. But there might be some benefit because HPR glass cracks into finer pieces than the earlier windshields. It is unreasonable to expect much effect on minor blunt trauma such as headaches, contusions or induced whiplash. Finally HPR windshields may reduce the types of ejections in which the occupant breaks through the glass while the periphery of the windshield remains attached to the frame; since this mode of ejection is rare, the overall reduction may be too small to measure.

1.5 Windshield installation methods

Prior to 1963, windshields were sealed inside a rubber gasket or molding which, in turn, was attached and sealed to the frame. It was a relatively loose attachment, both in the sense that the rubber gasket had some give to it in a low speed impact to the windshield and that the gasket could be partly or completely torn away from the car in a more severe impact.

Currently, windshields of domestic cars are directly bonded to the frame by an adhesive substance such as butyl rubber tape or a polysulfide, thiokol or polyurethane sealant. It is a more rigid attachment than the rubber gasket method, hopefully enhancing retention of the windshield in crashes and reducing the risk of ejection.

Adhesive bonding of the windshield was first applied to production vehicles on a trial basis on some of the 1963 Buick Specials and Oldsmobile F-85's. It became standard on all GM intermediates in model year 1964 and on all domestic cars by 1979. Many foreign models still used rubber gaskets as of 1979. Table 1-1 lists implementation dates for adhesive bonding by make, model and manufacturer. It is based on 5 publications by National Auto Glass Specifications, Inc., [3], [32], [33], [34], [38] corroborated by the author's observations of cars in numerous parking lots.

It is important to note that rubber gasket installations continued well past the 1/1/70 effective date of Standard 212, especially at Ford, Chrysler and most of the foreign manufacturers. When Ford discontinued its compact Falcon and introduced the Maverick in 1970, it actually switched back from adhesive bonding to rubber. The rubber gasket method used in domestic and Japanese cars is by no means a "pop-out" windshield. It can meet the Standard 212 compliance test (which allows up to 25 percent bond separation in a 30 mph barrier impact), as evidenced by continued use of this method in production cars after 1970. Also, tests by Trosien and Patrick indicated that even pre-1970 domestic cars with rubber gaskets could meet Standard 212 [50]. On the other hand, the rubber gaskets used in Volkswagens before 1970 was a much looser installation. The windshield had to be clipped to the metal frame in response to Standard 212.

TABLE 1-1

INTRODUCTION DATES FOR ADHESIVE WINDSHIELD BONDING (1960-79)
(Source: National Auto Glass Specifications, Inc. [3], [32], [33], [34], [38])

Corporation	Size Class	Model	Model Year/ Date Introduced
General Motors	Full-size (B and C body)		1965
	Intermediate (A, A special)	Chevelle, Tempest	1964*
		F-85, Buick Special	1963/64***
	Compact	Nova, etc.	1968
		Corvair only	1965
	Sports	Corvette	1968
	All others		*
Ford	Full-size	Ford, Mercury	1965
		Lincoln (except Mark)	1966
	Intermediate		1966
	Compact	Falcon (through 69)	1966
		Maverick, Comet (70-77)	**
		Fairmont, Zephyr	1978*
	Subcompact	Pinto, Bobcat	mid 1978
	Specialty	Mustang, Cougar	1969
	Luxury Specialty	Thunderbird	1967
	All others		*
Chrysler	Full-size		1969
	Intermediate		1971
	Compact	Valiant, Dart (through 76)	**
		Aspen, Volare	1976*
	Specialty	Barracuda	1970
		Charger (through 1970 only)	**
		Challenger	1970
	All others		*

*Always used adhesive bonding
**Always used rubber gasket
***Adhesive bonding on some cars in 63; all cars starting in 64

TABLE 1-1 (Continued)

Corporation	Size Class	Model	Model Year/ Date Introduced
AMC	Full-size		1967
	Intermediate		1967
	Compact	American (through 69)	**
		Gremlin, Hornet	1970*
	All others		*
Audi			1978
BMW			**
Capri (German)			**
Colt			Varies
Datsun		210	**
		710	*
		All others	Unknown
Fiesta			**
Honda			**
Mazda			*
Mercedes/Benz			**
Subaru			**
Toyota		Corolla	**
		Corona	**
		Celica	1978
Volkswagen			**
Volvo (1970-79 only)			*

*Always used adhesive bonding
**Always used rubber gasket

Since rubber gaskets could and did meet Standard 212, why did domestic manufacturers largely switch to adhesive bonding? Partly because adhesive bonding was felt to be even more effective than existing rubber gaskets in retaining the windshield. Also, it appears that adhesive bonding is a less costly installation method and offers a small weight savings (see Section 7.1).

If adhesive bonding enhances windshield retention and costs less, why did so many manufacturers persist in using rubber gaskets? Partly out of concern over reports that adhesive bonding significantly increases the injury risk of persons who are not ejected from the vehicle. This was the conclusion of the principal statistical study of windshield contact injuries [9] and it is a view widely held in Europe [44]. A major objective of this evaluation is to perform new analyses of the effect of bonding on the injuries of occupants who are not ejected. Also, it is possible that the rubber gasket may have advantages in terms of durability (the windshield is less likely to break loose from repeated travel over rough roads [4]), ease of repair, and in sealing out rain, wind or noise. In fact, the gasket is sometimes called a "weatherstrip" [13].

A secondary change in windshield mounting methods for domestic cars occurred when GM switched from butyl rubber type to a polyurethane sealant for the 1973 model year [29]; AMC switched in 1974 [31]. The newer method is believed to provide an even tighter bond than the tape [29]; this hypothesis will be tested in analyzing the NCSS data in Section 5.1.

Foreign manufacturers generally did not shift to adhesive bonding and continued to use rubber gaskets during the 1970's. Their persistent preference for rubber gaskets may date back to the era when especially hazardous, tempered glass windshields were allowed in many countries: it was more desirable for the windshield to pop out of its frame than to stay in place and injure the occupant [14]. It was reinforced by Rodloff and Breitenbuerger's research which suggested that, even with HPR glazing, a "controlled pop-out windshield" was needed [44]. Some of the rubber gaskets (e.g., in Japanese cars) were relatively tight and needed little or no modification in response to Standard 212. But the gasket on the pre-Standard 212 Volkswagen (and, possibly, some other German cars) was much looser than the types of gaskets used, for example, on American cars. Near the effective date of Standard 212, VW began to install continuous plastic clips between the rubber gasket and the pinchweld flange which constitutes the windshield's frame. That provided VW with a bonding method for its exports to the United States which met Standard 212 while retaining the rubber gasket method which they preferred and allowed them the option of continuing to use looser gaskets in cars sold outside the United States

When the analyses of this report were based on large data files (FARS, New York, Texas), the sample of German cars was limited to Volkswagen, where it is relatively clear that clips were installed very close to the beginning of the 1970 model year. For the smaller data files (NCSS, MDAI), the other German makes are included to increase the available sample size, even though it is not as well known when and if similar modifications were made. Thus, throughout the report, results on "German cars" are the ones based on NCSS and/or MDAI; those on "Volkswagen" are based on the other files. Practically speaking, though, the distinction is of minor importance since Volkswagen accounted for over 85 percent of the German cars sold here during 1965-75.

The potential benefits of adhesive windshield bonding are, of course, a reduction in the frequency and extent of windshield bond separation in crashes. In turn, this could reduce the likelihood of occupant ejection through the windshield and the number of fatalities associated with ejections.

The potential negative side effects of adhesive bonding could be manifold. Without a rubber gasket that stretches or tears away from the frame, the windshield may be more liable to cracking or tearing; if the former, there could be more minor lacerations; if the latter, more major lacerations and fractures. On impacts where the windshield is not penetrated, the lack of "give" in the windshield periphery could lead to more headaches, contusions and whiplash (at low speeds) or even concussions (at high speeds). But if, as some engineers believe [25], [50] windshields are a poor medium for transmitting impact forces to the frame, the effect of the mounting method could be negligible. Also, the effects could be different in pre-HPR windshields (which are penetrated at 10-15 mph) and HPR windshields (penetrated at 22-29 mph). It should be noted that Fargo's unfavorable results concern the effect of bonding in pre-HPR windshields, only [9].

1.6 Evaluation objectives and limitations

Three statistical analyses of accident data constitute the bulk of the evaluation:

- The effect of HPR windshields on the risk of an occupant being injured by contact with the windshield--Chapter 4.

o The effect of windshield installation method on the risk of occupant ejection through the windshield portal--Chapter 5. The effects of adhesive bonding in domestic cars and of clipped rubber gaskets in Volkswagens are analyzed separately.

o The effect of windshield installation method on the risk of an occupant being injured by contact with the windshield, while remaining in the vehicle--Chapter 6. Adhesive bonding in domestic cars with HPR windshields, adhesive bonding in domestic cars with pre-HPR windshields and clipped rubber gaskets in Volkswagens (with HPR windshields) are analyzed separately.

The strategy of this evaluation is to perform, in each chapter, parallel "injury" and "engineering" analyses of accident data. In Chapter 4 (HPR), the "injury" analysis of the reduction of various types of head trauma is paralleled by an "engineering" analysis of the velocities at which heads penetrate windshields in crashes. The increase in the penetration velocity is the engineering explanation of why injuries characteristically associated with penetrated windshields were mitigated. In the study of the effect of the windshield installation method on ejection (Chapter 5), the "injury" analysis of occupant ejection risk is accompanied by an "engineering" analysis of windshield separation in crashes: ejection risk ought to be proportional to the frequency or amount of windshield separation. The analysis of the side effects of the windshield installation method on occupants who were not ejected (Chapter 6) again compares types of head injuries and penetration velocities.

Since there are a variety of windshield injury mechanisms resulting in quite different injury types, a separate "injury" analysis is conducted for each of the major types of windshield-caused injuries--serious lacerations, fractures, concussions, minor lacerations, headaches and contusions--as well as for all types combined. The analysis by type of injury will assist the "engineering" analysis in showing why windshields are preventing the injuries as well as giving an estimate of net benefits.

When the accident data specify both the injury type and injury source (NCSS or MDAI), the analysis focuses on injuries specifically due to contact with the windshield. When the data specify injury type, but not the source (New York State), the analysis focuses on head, face and neck injuries of front-seat occupants in frontal crashes, which is where most windshield contact injuries occur. If the injury type is also unknown (Texas, FARS), front-seat occupant casualty risk in frontal crashes is analyzed by severity level only, sometimes using nonfrontal crashes as a control group.

Most of the time the analytic approach is to compare the injury risk of occupants of cars of the first model year equipped with HPR/adhesive bonding/clipped rubber gaskets to the risk of occupants of cars of similar makes and models of the last model year before HPR/adhesive bonding/clipped rubber gaskets. Next, cars of the first 2 years with HPR/adhesive bonding/clipped rubber gaskets fare compared to the last 2 years without it; then a comparison for ± 3, ± 4, ± 5 years. This approach has proven successful in previous evaluations [20], [21] for differentiating the actual effect of the safety equipment being studied from the effects of other safety improvements or data biases. A multivariate analysis of injury severity, windshield type, and control variables would be inappropriate: in the police-collected data files, because suitable control variables are unavailable; in NCSS, because the sample size for pre-standard crashes is too small for further parsing by control variables.

The analyses will estimate the reduction in the number of persons injured each year, by injury type, if each car in the United States is equipped with HPR windshields relative to the baseline situation in which all cars were still equipped with the pre-standard windshields; if each American car is equipped with adhesively bonded HPR windshields relative to a baseline of gasket-mounted HPR windshields; if each Volkswagen is equipped with clipped rubber gaskets and HPR glazing, relative to a baseline of pre-Standard 212 gaskets and HPR.

Likewise, the cost of a windshield improvement is the average incremental cost per car for the improvement multiplied by the number of cars sold in the United States in a year. The cost increment includes the increase in the initial purchase price and the incremental fuel consumption over the life of the vehicle.

The evaluation is limited to windshield modifications that have actually been implemented to date (October 1984) on large numbers of production vehicles sold in the United States. In particular, glass-plastic glazing materials such as Securiflex are not evaluated because their on-the-road experience in this country is limited to small test fleets. It should be noted, though, that laboratory tests have suggested glass-plastic glazing may have great potential for reducing the number of minor lacerations--and this evaluation shows that 427,000 minor facial lacerations are still occurring annually, even after HPR. It may also be useful especially in side-window applications, for reducing ejection through glazing (see Clark and Sursi, "The Ejection Reduction Possibilities of Glass-Plastic Glazing, SAE Paper No. 840390, 1984).

The evaluation is limited to passenger cars. Trucks did have to meet Standard 205 in 1968, but there are few pre-Standard 205 cases on the data files used in this evaluation. Most of them continued to use rubber gaskets until the late 1970's so there are hardly any cases with adhesive bonding. A paper by Najjar titled "FMVSS No. 212 and 219; Aggressiveness, Downsizing and Ejection" (NHTSA, 1980, DOT HS-805 883) considers windshield installation methods in vans. (After NHTSA extended Standard 212 to light trucks and vans, effective 9-1-78, the manufacturers began shifting from rubber gaskets to adhesive bonding. NHTSA also sought and obtained written commitments from the manufacturers to use adhesive bonding in trucks and vans at that time.)

The evaluation is limited to the windshield and does not discuss side windows or other glazing. In about 1960, there was a shift from laminated (pre-HPR) to tempered side windows. If appropriate accident data had been available, it would have been worthwhile to analyze the safety consequences (not necessarily positive) of that shift. But the number of side window-related injuries in cars of that age on NHTSA accident files is entirely insufficient for meaningful statistical analysis.

The available sample sizes were too small in NCSS for statistically significant results on some of the types of injury. Therefore, NCSS was supplemented with analyses of New York State data on types of head injuries; NCSS and Multidisciplinary Accident Investigation data were used in combination for the analysis of ejection through the windshield portal. With the addition of these data sources, the samples were more than adequate for showing that the HPR windshield and tighter windshield installation achieved their primary objectives with little or no side effects.

CHAPTER 2

EARLIER STUDIES OF WINDSHIELD GLAZING AND MOUNTING

There have been a large number of laboratory studies of windshields as well as a few accident analyses. Windshields lend themselves especially well to laboratory testing because the procedures are inexpensive and the measurement criteria are straightforward. This review is confined to the studies that specifically evaluate HPR glazing or adhesive bonding. The studies unequivocally indicate that HPR glazing is effective but are inconsistent about adhesive bonding: some of them show that the mounting method makes little or no difference while others show a substantial negative side effect for adhesive bonding.

2.1 Laboratory studies of HPR windshields

The principal tools for testing windshields are the drop test and the chamois. Various objects are dropped onto samples of windshield glazing from a range of heights and the threshold velocities at which various types of breakage occur are measured. In particular, the penetration velocity is the most important measurement because most of the serious injuries in pre-HPR windshields are a result of penetration (see Section 1.3). If the projectile is equipped with accelerometers, the deceleration-time history can be obtained. In some cases, a sled test using dummies and a vehicle's passenger compartment is substituted for the drop test because it allows a more realistic simulation of the dummy head kinematics. Chamois is a thin goat skin whose laceration properties are similar to human skin. Two layers of it are wrapped around the dummy headform. The number and depth of lacerations in the chamois are used to measure the laceration risk for human beings in actual crashes.

2.1.1 Patrick and Daniel (1964)

The research was sponsored by Ford and conducted at Wayne State University [41]. Sled tests were run with instrumented unrestrained cadavers and dummies. The pre-HPR windshield was penetrated in all tests with head-to-glass contact of 14 mph or more, always resulting in AIS $\geq$ 2 lacerations. There were multiple facial bone fractures on the 24 mph head-to-glass contact, directly attributable to the penetration.

The HPR windshield was not penetrated in head-to-glass impacts up to 29 mph. There were no lacerations below the 16-29 mph range. Serious lacerations and facial bone fractures occurred only on the 29.3 mph impact which resulted in penetration.

Deceleration of the cadaver head was substantially lower for the HPR windshield than for the pre-HPR glass in the 13-29 mph range--i.e., where only the pre-HPR windshield was penetrated--because, according to the authors, it is the contact with the exposed edges at the hole in the windshield which causes the most severe deceleration. For example, at 20 mph, head deceleration was about 100 g's for pre-HPR and 50 g's for HPR.

In other words, the HPR windshield greatly reduced the risk of serious lacerations without increasing deceleration values.

2.1.2 Rieser and Michaels (1965)

The research was performed at the Pittsburgh Plate Glass Co., which played a major role in the development of the HPR windshield [42]. Five-pound steel balls and 22 pound chamois-covered headforms were dropped onto relatively small panels of pre-HPR and HPR glazing. The low cost of the test procedure allowed extensive replication of tests and a precise calculation of the mean penetration velocity. These velocities, as a function of type of glazing, type of projectile and the angle between the plane of the glass and a vertical line were:

	5 lb. Steel Ball		22 lb. Headform	
	45°	90°	45°	90°
pre-HPR	13 mph	9	14	10
HPR	26	26	28	28

It is evident that the 5-pound steel ball and 22-pound headform correlated well in these tests. Both are used to simulate the interaction of the head of a lap-belted cadaver with the windshield. Clark of NHTSA, however, feels that the 5-pound ball might not perform as realistically on windshields with thinner glass layers than the ones used during the 1960's.

In all cases, the HPR glass had 2-3 times as high a penetration velocity. The results for the 45 degree tests are nearly the same as Patrick and Daniel's cadaver results, indicating that drop tests with small glass panels adequately model real-life performance.

Other types of glazing material were also tested. Polyvinyl butyral alone (without glass) had a penetration velocity well above 30 mph even when only the 0.015 inch pre-HPR plastic was used. This shows that the vulnerability of windshields at much lower speeds is not to be blamed on the weakness of the plastic but rather on the way it interacts with broken glass. Glazing which used 1/8 inch layers of tempered glass in combination with polyvinyl butyral had higher penetration velocities than the HPR windshield but it produced dangerous head deceleration levels at subpenetration velocities.

2.1.3 Widman (1965)

The effects of various parameters on penetration velocity were tested at Ford [52]. Drop tests were conducted with a 22 pound headform. The HPR interlayer not only has lower adhesion to glass than the pre-HPR interlayer, it is also twice as thick. Widman tested separately the effects of plastic type and thickness on penetration velocity:

	0.015 inches	0.030 inches
pre-HPR	9 mph	13
HPR	13	22

Use of an HPR interlayer provides a significant benefit even at the old thickness of 0.015 inches but yields an even greater gain at 0.03 inches.

Widman also demonstrated that increases in moisture content lead to increases in penetration velocity, but only for the type of plastic used for the HPR interlayer and that, only up to 0.6 percent moisture content. Thus, the optimal material is the HPR interlayer with moisture content controlled to be close to 0.6 percent.

2.2 Laboratory studies of windshield mounting techniques

Two German studies indicated a significantly higher penetration velocity for windshields mounted with rubber gaskets than for adhesively bonded windshields. Two American studies showed only marginal differences. The rationale for a large difference is that the stretching of a rubber gasket or its controlled separation from the frame can absorb a significant portion of the impact energy applied to the windshield by the occupant's head and transmitted to the frame by the elastic interlayer--or that the popout of the windshield virtually eliminates the head/glazing interaction. The rationale for a marginal difference is that windshield glazing, even with a plastic interlayer, transmits force poorly to the windshield periphery; the primary force on the head is due to the inertia of the glass in the localized impact area. Under these circumstances, it is important to review the test procedures of the various studies in detail, because they may strongly influence the likelihood that forces are transmitted to the periphery.

2.2.1 Rodloff and Breitenbuerger (1967)

The research was performed at the German Plate Glass Co. [44]. Dr. Rodloff, 5 years earlier, had been instrumental in the development of HPR glass. Drop tests were conducted using a 22 pound headform and 20 x 30 inch panels of glazing. The glazing samples used an HPR interlayer of varying thickness. The penetration velocities, as a function of mounting method and interlayer thickness were:

	0.02 inch HPR	0.03 inch HPR (Standard
Rubber gasket	24 mph	>36
Adhesive bonding	18	24

Several factors may have contributed to this remarkable increase in penetration speed for the rubber gasket. One is that the rubber gaskets were typical of German vehicles of the 1960's: loose enough to allow the glass to pop out easily. (This explanation assumes that the authors counted a glazing sample which popped out and let the headform pass through open space as a "nonpenetrated" sample--a "success.") A second is that the glazing samples were smaller than real windshields. Since the distance from the contact area to the the perimeter is shorter, forces are more readily transmitted to the frame. Another possibility is that the rubber gasket used here was even looser than those used in German production vehicles, especially so if the rubber was still fresh at the time of the test.

The authors concluded that adhesive bonding "defeats a great part of the improvements achieved" by the HPR windshield.

2.2.2 Patrick (1968)

The research was performed at Wayne State University in preparation for a European safety conference [40]. Its specific objective was not to determine the penetration velocity but rather to identify the effect of mounting technique in head and neck injury risk at lower velocities. Sled tests were performed using unrestrained dummies and cadavers. The sled buck was crafted from a Volkswagen sedan (a small European car for which rubber gaskets were standard equipment). HPR windshields were tested under 3 mounting conditions:

- o Basically unattached to the car
- o Standard VW rubber gasket
- o Butyl tape

Test speeds ranged from 9 to 24 mph and did not result in head penetration on any test.

The rubber gasket installation allowed the windshield to pop out on most tests and the results resembled the basically unattached condition (As described earlier, the gasket used at that time by VW was much looser than those used in the United States, especially when the rubber was fresh.) Nevertheless, there was little or no difference in the head severity indices or neck rotations due to windshield contact between the butyl taped windshields and either of the loose mounting conditions. In fact, these indices were always well below the threshold for significant injuries. On the contrary, when windshields popped out, there was potential for significant injuries due to contact with the exposed windshield frame or the car's hood.

Although penetration did not occur on any test, there were small tears in the interlayers under all 3 conditions. The tears began to happen at about the same speeds or, perhaps, at marginally lower speeds in the taped windshields.

Based on these results, Patrick indicated a preference for adhesively bonded windshields. Patrick's results are not directly comparable to Rodloff and Breitenbuerger's because his tests were all conducted at 24 mph or less, which would not have caused penetration in their tests, either. The issue of penetration speeds remained to be addressed in the next study.

2.2.3 Trosien and Patrick (1970)

Chrysler Corporation sponsored this research at Wayne State University [50]. Chrysler did not begin changing over from rubber gaskets to adhesive bonding until 1969, at which time GM had completed the transition. Sled tests were performed with instrumented unrestrained dummies in a sled buck built from a 1964 Plymouth. HPR windshields were tested under 3 mounting conditions

- o Standard Chrysler rubber gasket
- o Butyl tape
- o Polysulfide (Thiokol) pumped adhesive

Test speeds ranged from 20 to 30 mph, resulting in occurrences of penetration for all three conditions.

Mean interlayer tear and head penetration velocities were:

	Interlayer Tears	Penetration
Rubber gasket	25 mph	30
Butyl tape	24	30
Polysulfide adhesive	23	25

These velocities may contain some sampling errors because they are based on a relatively small number of sled runs (8 in each mounting condition). In any case, though, they only show moderate differences between rubber gaskets and the two types of adhesive bonding. Contrast these results with Rodloff and Breitenbuerger, who found that adhesively bonded HPR glass was penetrated at 24 mph and the glass in rubber gaskets, not even at 36 mph (possibly because the whole windshield came out in the latter case).

Trosien and Patrick also recorded the amount of separation of the windshield from its periphery on each test. There were no significant differences between rubber gaskets and adhesively bonded windshields. The most extensive pullout on any test was about 15 percent and it occurred with a butyl taped windshield. The average amount of pullout per test was just over 1 percent. The bond remained intact in 19 of their 23 tests. Although these findings cannot be directly compared to the Standard 212 requirements, which are based on a barrier impact rather than a sled test, they seem to indicate that rubber gasket mountings commonly used in the United States, even as early as 1964, probably could have met Standard 212.

The discrepancies between this study and the European results are best explained as follows:

o American rubber gasket mountings appear to have been tighter than European ones of that era, at least the ones used in the tests. Thus, the difference between gaskets and adhesive bonding is less pronounced here.

o Trosien used a full windshield whereas Rodloff used smaller glass samples. The larger the glass area, the harder it is to transmit forces to the periphery.

o Perhaps, the dummy head kinematics in Patrick's sled tests produced more localized forces on the glass than Rodloff's 22 pound headform.

The authors calculated the laceration index and the head severity index (for blunt trauma) on each test. Lacerations were approximately equal for rubber gaskets and butyl tape and marginally higher for polysulfide adhesive. Blunt trauma was more or less the same for all three conditions and well below dangerous levels in every case.

They ran about a quarter of the sled tests with the car's instrument panel removed. It seemed to have little or no effect on head-windshield interaction or injury risk, suggesting that windshield performance may be relatively insensitive to changes in the design of other components of the vehicle. The angle of the dummy head at impact was recorded on each test (but could not be controlled in advance). When the dummy's head was tilted down, the momentum of its upper torso was also applied to the windshield, tearing the interlayer at a lower speed. In fact, head angle was more important than windshield mounting method as a factor in windshield performance.

Trosien and Patrick found the differences in the test results too small to warrant recommending one windshield installation method over any of the others, in cars equipped with HPR windshields.

2.2.4 Seiffert, Hildebrandt and Nitzsche (1972)

Engineers at Volkswagen tested the effects of various parameters on penetration velocity [48]:

- o Windshield mounting method
- o Thickness of the interlayer
- o Thickness of the inner and outer glass layers

Windshield samples were struck by a 15 pound pendulum device, a 22-pound free-flying headform launched from a cylinder by a piston, two headforms dropped simultaneously from a tower, or an unrestrained dummy riding a sled.

The samples of windshield glazing used in the tests were 15 x 40 inches, which is smaller than a production windshield. Moreover, the samples used in the tests of windshield mounting methods contained an 0.045 inch HPR interlayer, which is 50 percent thicker than the ones in production HPR windshields. Loose and rigid mounting methods were simulated by clamping the glazing samples to a frame with clamp pressures ranging from 28 to 225 psi.

Under these conditions, penetration speed was 47 mph for windshields clamped at 28 or 56 psi and 40 mph with the 225 psi clamping. Whereas this is a significant reduction in penetration velocity for rigid bonding, the results are not inconsistent with Trosien and Patrick's. Seiffert et al's combination of a smaller than normal glazing sample with a thicker than normal interlayer would tend to accentuate the transmission of force from the contact area to the perimeter. If full windshields with the ordinary 0.03 inch plastic had been used, the difference would probably have been smaller in both absolute and relative terms.

2.3 Analyses of highway accident data

2.3.1 Fargo (1968)

R. B. Fargo of Calspan Corporation performed a detailed evaluation of windshield glazing and mounting [9]. In fact, it is one of the outstanding statistical analyses in the field of highway safety. For that reason, its unfavorable results on adhesive bonding have to be given serious consideration and cannot be quickly written off to inadequate sample size, obvious biases or inappropriate analysis techniques.

The study is based on Automotive Crash Injury Research (ACIR) data. ACIR was an important National accident data file, collected during 1953-69. Police from several States were specially trained to collect detailed injury, contact point and crash severity data. Although they did not use probability sampling techniques, they collected a large and fairly uniform sample of injury-producing accidents involving then-recent American vehicles.

Fargo obtained a sample of 2292 cars of model years 1964-67 which had sustained frontal impacts in crashes where at least one person was injured. There were 3480 front-seat occupants in those cars. (Although this is a smaller N than the NCSS data used in this report, the high injury rates and low missing data rates for contact points on ACIR imply that ACIR results actually have a better chance for statistical significance than NCSS results for pre-1970 cars.)

In order to make valid pre-post comparisons, Fargo drew 3 (partially overlapping) subsamples from his ACIR data:

I. MY 1964 cars with rubber gaskets and pre-HPR glass and MY 1965 cars of the same makes and models with adhesive bonding and pre-HPR glass (primarily full-sized Ford and GM cars). This subsample is used to measure the effect of changing from gaskets to adhesive bonding in pre-HPR cars.

II. MY 1964-1965 cars with pre-HPR glazing and rubber gaskets and MY 1966-67 cars of the same makes and models with HPR glazing and rubber gaskets (all Chrysler Corporation cars, Mustang, Chevy II, etc.)--used to evaluate the effect of HPR glass in rubber gasket cars.

III. Pre HPR MY 64-65 cars with adhesive bonding and post-HPR MY 66-67 cars of the same makes and models with adhesive bonding (intermediate GM plus full-sized 65-67 GM and Ford)--used to evaluate HPR glazing in adhesively bonded cars.

It was impossible, however, to perform the 4th comparison, i.e., to evaluate the effect of changing from gaskets to adhesives in post-HPR cars because, as of 1967, there was no group of high-volume post-HPR makes and models with gaskets one year and adhesives the next.

Fargo's statistical procedures of isolating the effects of glazing from those of windshield mounting, and limiting his data sets to cars of identical makes and models built within two years of the date of a safety modification are excellent. They should minimize biases and confounding factors. Furthermore, in order to remove possible biases due to ACIR's nonprobability sampling scheme, Fargo post-stratified (or standardized) the data by crash severity, belt usage and vehicle occupancy/seat position.

The first analysis pertains to windshield damage patterns. Fargo's "web-broken" category corresponds to significant tears and/or penetration of the interlayer by an occupant's head. The percent of cars involved in frontal crashes which had "web-broken" damage were

	Pre-HPR		HPR	
Group	Rubber	Adhesive	Rubber	Adhesive
I	10.6 →	17.9		
I	17.0 →	→	2.4	
III		18.9 →	→	2.3

All of the observed changes are statistically significant. The 69 percent increase in web-broken damage in Group I suggests that adhesive bonding significantly lowered penetration velocity in pre-HPR cars. The stunning 86 percent and 88 percent reductions in Groups II and III, respectively, indicate that HPR glazing greatly increased penetration velocities, regardless of the windshield installation method. The benefit of HPR glazing clearly outweighs the effect of the mounting method, when it comes to windshield damage patterns.

The most basic measure of effectiveness is the percentage of occupants with AIS $\geq$ 2 head injury attributable to windshield contact:

	pre-HPR		HPR	
Group	Rubber	Adhesive	Rubber	Adhesive
I	11.1 →	15.9		
II	17.1 →	→	5.2	
III		17.0 →	→	8.9

Again, all changes are statistically significant. Pre-HPR cars with adhesive bonding had a 43 percent higher windshield injury risk than comparable pre-HPR cars with rubber gaskets. The HPR windshield was very effective in rubber gasket cars, reducing injuries by 70 percent. It was somewhat less effective in cars with adhesive bonding, reducing injuries by 48 percent. Groups I and III have a large overlap, since both contain full-sized GM and Ford cars. The Group III cars with both HPR glazing and adhesive bonding have an injury rate only 20 percent lower than the Group I cars with neither. These statistics are consistent with Rodloff's conclusion that adhesive bonding defeats a great part of the improvements achieved by the HPR windshield (see Section 2.2.1).

Fargo also analyzed effectiveness by injury type (laceration, concussion, fracture) and/or specific location (eye, face, forehead, scalp). The results were homogeneous across injury types; negative for bonding; positive for HPR, especially in rubber gasket cars. For example, adhesive bonding (in pre-HPR cars) increased the risk of concussion, facial fracture, and soft tissue injuries of the face, forehead and scalp. The effect on eye injuries and skull fractures was unclear. HPR glazing reduced eye injuries and concussions (definitely on gasket mounted windshields, probably on bonded ones), facial fractures, and all external soft tissue injuries. The effect on skull fractures was unclear. In general, all of these trends on injury risk can be attributed to the change in penetration velocity: as the laboratory studies showed, windshield penetration increases laceration risk and impact force (fractures, concussions). Thus, the combinations with higher penetration velocities scored better on nearly all of the injury categories defined by Fargo.

The analysis by injury type could have been made more useful if soft tissue injuries characteristic of windshields with torn interlayers (AIS $\geq$ 2 lacerations and avulsions) had been separated from those generally associated with cracked windshields whose interlayer was not torn (minor lacerations, abrasions). As this report will show, there are big differences in effectiveness between those two categories. The analyses also did not consider injuries due to ejection through the windshield portal or neck injuries induced when the head contacts the windshield.

2.3.2 Discussion of Fargo's results

What happened in the highway safety community in the years following Fargo's sharp indictment of adhesive bonding? European researchers, of course, cited it as corroboration of their laboratory tests which showed rubber gaskets to be superior [48]. European and Japanese manufacturers continued to use rubber gaskets in most of their cars throughout the 1970's (although it is unknown to what extent that decision was based on Fargo's study or other results). In the United States, the transition from rubber gaskets to adhesive bonding, which had been brisk in the mid 60's, slowed down (again, not necessarily because of Fargo's study). Ford even shifted back to rubber gaskets on its compact cars in 1970.

Most significant, perhaps, was Chrysler's sponsorship of Trosien and Patrick's laboratory study of injury potential as a function of windshield installation method (see Section 2.2.3). The laboratory tests did not show any significant adverse effects for bonded HPR windshields relative to rubber-framed HPR windshields. Fargo's result, of course, was for pre-HPR windshields.) At that time and in the years that followed, Chrysler Corporation shifted its production from rubber gaskets to adhesive bonding.

Trosien and Patrick reviewed Fargo's results in the introduction to their paper [50]. They stated that Fargo found "small but significant" injury increases for adhesive bonding. In fact, Fargo observed a highly significant 42 percent increase. They criticized him for not considering changes in the instrument panel or passenger compartment layout that coincided with the transition to adhesive bonding. But a few pages later in their report, Trosien and Patrick observed that complete removal of the instrument panel made little or no difference in their own laboratory test results. They criticized ACIR data because injuries caused by other contact points may have been misclassified as windshield injuries. But it is hardly possible that such misclassifications occurred so much more often for bonded windshields; moreover, the concern about misclassification raised by Huelke [16] and Herman and Garrett [15] applies mainly to serious blunt trauma, not to the lacerations that predominate in Fargo's data.

Since Trosien and Patrick's criticisms do not appear supportable, how can the discrepancy between their results and Fargo's be explained?

One possibility is that adhesive bonding really did increase injury risk on pre-HPR windshields (as found by Fargo) but not on HPR windshields (Trosien and Patrick). This is intuitively difficult to believe. But perhaps, at the very low speeds needed to break a pre-HPR windshield, the extra "give" in the rubber lining might really make a difference. At the high speeds needed to break an HPR windshield, local forces will shatter the glass and tear the interlayer before any significant amount of energy is absorbed by stretching or pulling out the gasket.

Another possible factor may be found in the nonprobability sampling scheme of ACIR. In Fargo's Group I, used for comparing adhesive bonding to rubber gaskets, the latter are all in 1964 models, the former in 1965 cars. ACIR data are generally collected only for late model year cars. Thus, the accident data for MY 64 cars was collected mostly in 1964, the MY 65's mostly in 1965. If different police agencies, reporting quotas, interpretations of "injury", etc., were used in those 2 years, injury rates could be different. The data in Fargo's report appear to indicate that more accidents were reported to ACIR in 1964 than in 1965 and that the injuries were, on the average, less severe in 1964. This could explain why the 1965 models (with adhesive bonding) fared so much worse than the 1964 models (with gaskets). If Fargo had included any data on injuries caused by components other than windshields, this hypothesis could have been tested directly. In the absence of such data, the evidence for the hypothesis includes:

o The higher reporting rate for MY 64 than for MY 65 cars (p. 21 of Fargo's report)

o The "framed pre-HPR Group II", injury rate, which includes MY 64 and 65 cars is much higher than the "framed pre-HPR Group I," which includes only MY 64. In fact, it is as high as the "bonded pre-HPR Group I" (p. 37) o In the analysis by type of injury, bonded windshields do worse on all types of injury, by about equal amounts. This could be more indicative of a systematic data bias than a specific effect of adhesive bonding (p. 51)

2.3.3 Huelke et al (1968)

A clinical accident analysis based on 6 cases showed HPR windshields to be effective [17]. Huelke et al selected from the Highway Safety Research Institute's files 3 in-depth investigations of frontal impacts with Delta V approximately 10, 20 and 30 miles per hour respectively. In all cases the front-seat occupants penetrated the pre-HPR windshield and sustained nonminor head injuries. Next, they selected 3 accidents with HPR windshields that closely matched the first 3, except that Delta V's were slightly higher (about 15, 25 and 35 mph). The occupants did not penetrate the windshield and had only minor head injuries due to windshield contact. The study presents detailed analyses of injury mechanisms in the individual cases.

2.3.4 Anderson (1972)

T. E. Anderson calculated occupant injury rates, by contact points, in model year 1960-65 cars in the ACIR file [2]. He compared them to rates for MY 1968-71 cars on the Calspan Level 3 in-depth accident investigation file. Since the first group was built before the major safety modifications of the 1966-68 era and the second one afterwards, the comparison is used to evaluate the benefits of the major safety standards. The analyses are biased against the post-standard cars because the Calspan Level 3 data, while outwardly resembling the sampling scheme for ACIR, tended to have considerably higher injury rates in accidents of the same "severity." As a result, lap belts, energy-absorbing steering columns and head restraints were all observed to increase injuries [19], p. 133. Under these circumstances, it is especially impressive that HPR windshields reduced nonminor head injuries due to windshield contact by a statistically significant 41 percent (combining across severity groups on [2] p. 76). The effectiveness of 41 percent is surely understated, in view of the negative results on other standards.

2.4 Summary

Laboratory studies and accident analyses unanimously indicated that the HPR windshield is highly effective. It remains for this evaluation to determine how many injuries of various types are eliminated by HPR.

Trosien and Patrick's laboratory study did not show a substantial difference between rubber-framed and adhesively bonded HPR windshields. All the other studies showed significant negative effects for adhesive bonding but they were based on pre-HPR windshields, gaskets that are looser than those used in the United States, thicker-than-normal interlayers and/or smaller-than-normal pieces of glass. A major objective of this evaluation is to resolve whether adhesive bonding has significant adverse effects, for persons who are not ejected, in current production vehicles (with HPR glazing) involved in highway accidents.

None of the earlier studies addressed in depth the question of whether adhesive bonding enhances windshield retention or prevents occupant ejection in crashes. That remains a major task of this evaluation.

CHAPTER 3

DATA AND ANALYSIS TECHNIQUES FOR EVALUATING WINDSHIELDS

The statistical analyses of Chapters 4-7 all employ the accident files and data definitions described here.

3.1 Data needs and guidelines

The study's objective is to find the effect of HPR glazing and adhesive bonding of the windshield on the injuries of occupants of crash-involved domestic passenger cars and the effect of clipping the rubber gasket on the injuries of Volkswagen occupants. (The data files contain too few cases of imported cars or light trucks with pre-HPR glazing or adhesive bonding to warrant the inclusion of these vehicles classes in the analyses of those vehicle modifications.)

o Each car on the data files needs to be identified as to its type of glazing and method of windshield mounting. The identification is based on the make, model and model year of the car. For example, all domestic cars had HPR windshields beginning in 1966, except Ford Thunderbird in 1965. The introduction dates for adhesive bonding are shown in Table 1-1. The introduction dates for the other changes in windshield mounting are: clips to hold the windshield, on Volkswagens starting in 1970; polyurethane sealant at GM in 1973 and AMC in 1974. Furthermore, most of the analyses of Chapters 4-6 are based on a restricted age range of cars--e.g., all cars of the last 2 model years before adhesive bonding was introduced vs. all cars of comparable makes and models of the first 2 years with adhesive bonding. Thus it is necessary to calculate, for each car on the file, the difference between that car's model year and the introduction year for HPR glass/adhesive bonding/clipped rubber gaskets on that make and model or a "comparable" one. For example, a 1969 Chevrolet Nova was built 1 year after the introduction date for adhesive bonding in Novas (1968, from Table 1-1) and 3 years after the HPR windshield was introduced.

What are "comparable" makes and models? In general, they are cars of the same manufacturer and size/market class, preferably sharing the same body platform. In most cases, Table 1-1 makes it clear what are comparable cars. For example, a 1974 Oldsmobile Omega is a GM compact car which is obviously comparable to a Nova, not a Corvair; thus, it was built 6 years after the introduction date for adhesive bonding (1968). The only make/models requiring special rules or explanation are the following:

- Cars which always had adhesive bonding and for which there was no comparable model with rubber gaskets are excluded from the analysis of adhesive bonding (but not from the analysis of HPR windshields). Those cars include Buick Riviera; Cadillac Seville; Chevrolet Camaro, Vega and Chevette; Ford Granada; Lincoln Mark; Chrysler Cordoba; Dodge Omni; AMC Marlin and Javelin; and their twins in other divisions.

- GM intermediates (Buick Special, Chevrolet Chevelle and Monte Carlo, etc.) and Ford subcompacts (Ford Pinto and Mercury Bobcat) are likewise excluded from the Standard 212 analysis. Although some of the former were produced with gaskets (till mid 1963) and some of the latter with bonding (after mid 1978) there are so few of these cases on the data files used here that, for all practical purposes, all cars used the same windshield mounting technique.

- Ford Fairmont is deemed to be comparable to Ford Maverick for the purposes of this report; the two models are retained in the Standard 212 analysis and are treated as a single model with 1978 as the initial year of adhesive bonding. Similarly, Dodge Aspen is comparable to Dart, with adhesive bonding introduced in 1976; Dodge Charger up to 1970 is comparable to Challenger (bonding in 1970); Charger is comparable to Coronet starting in 1971 (bonding in 1971); AMC Gremlin and Hornet are both comparable to American (bonding in 1970); their twins in other divisions are similarly handled. In some cases, it can happen that a car with rubber gaskets was sold after the "introduction date" for adhesive bonding--e.g. 1976 Dodge Darts and 1970 Dodge Chargers, according to the above definitions. These cars are included with "cars of the last model year before bonding" in the analyses of this report since they are essentially leftovers from the previous year's model run.

o Each occupant in the data files needs to be classified according to the presence or absence, type and severity of injuries involving the windshield. When the data file specifies the contact sources of injuries (NCSS or MDAI), it is straightforward to select those injuries attributed directly to windshield contact plus those that may be indirectly related: outside-the-car injuries of persons ejected through the windshield portal and noncontact neck injuries of persons whose head contacted the windshield (see Section 1.3). If contact points are not specified, but the body region and type of injury is coded (New York), the analysis is based on the head, neck and facial injuries of front-seat occupants in frontal crashes--the type of injury that is by far the most likely to have been caused by windshield contact. If the body region and type of injury is also unspecified (Texas, FARS) the analysis is based on injury rates of front-seat occupants in frontal crashes or on a comparison of frontal crashes (where most of the windshield-caused injuries occur) to a control group of nonfrontal crashes (where few of them occur). In all of these analyses, then, it is necessary to identify the occupant's seat position and the vehicle's crash mode.

o For analyses of why the standards have affected injury risk, it is desirable to know the velocities at which occupants' heads penetrated the windshields. The exact velocities are, of course, unknown in highway accident data. A surrogate is obtained by using the vehicle's velocity change (Delta V), because the unrestrained occupant's head will often strike the windshield at a velocity close to Delta V in a frontal crash.

o For the evaluation of Standard 212, it is necessary to have information on windshield retention and occupant ejection in crashes. Windshield performance is expressed by the percentage of the periphery that has become separated from its bond. Ejection information should ideally include the ejection portal: that would make it possible to study ejections through the windshield portal separately. When information on the ejection portal is unavailable, the approach is to compare ejectees to a "control" group of nonenected occupants. It is also desirable to know whether an occupant was completely or partially ejected.

o For regression analyses of injury or fatality risk, it is desirable to have data files from multiple calendar years in order to reduce the correlation between two independent variables: windshield type and vehicle age. In other words, there should be some old vehicles with post-standard windshields and some relatively new ones without them. Only Texas and FARS data were available for multiple calendar years; they are the only files used in the regression analyses of injury or fatality risk.

3.2 National Crash Severity Study

Since 1977, the National Crash Severity Study (NCSS) has been a primary source of detailed information on vehicle and injury performance in highway accidents involving passenger cars. NCSS is a probability sample of 12,050 towaway accidents which occurred during 1977-79 and were investigated by 7 multidisciplinary teams. A detailed description of NCSS may be found in [18], pp. 138-149 and in [39].

NCSS uses a 5 digit make/market class code [39], pp. 8-9 - 8-14, which, in most cases, is readily transformed into the make/model groups shown in Table 1-1. In a few cases, cars with different windshield mounting methods had the same NCSS code and had to be identified by analyzing the Vehicle Identification Number (VIN), which was also coded in NCSS--e.g., Chevrolet Corvair and Nova, Dodge Charger and Challenger (in 1970).

NCSS codes the injury location, type, severity and contact source for up to 6 injuries per occupant. If a person was ejected, the ejection portal is also coded. Windshield-related injuries (up to 6 per occupant) are assigned to the following categories:

o Windshield contact injuries (contact code is the windshield)

- Nonminor facial or scalp lacerations: body region is head or face; lesion is laceration or avulsion; system/organ is not the brain; AIS $\geq$ 2. The category includes injuries to the eyes, nose or mouth; occasionally they are specially analyzed as a separate category. It excludes "lacerations" of the brain or spinal cord, which are not the ordinary type of injury caused by broken glass.

- Facial or skull fractures: body region is head or face; lesion is fracture; AIS $\geq$ 2. Few of them are skull fractures. Some are nasal fractures.

- Minor lacerations: same definition as "nonminor lacerations" above, except that AIS = 1.

- Concussion: any lesion whose system/organ is the brain and AIS $\geq$ 2. Basically, closed head injury.

- Minor blunt impact trauma: any minor windshield contact injury of the face or head other than the above, except neck injuries. Mostly contusions, abrasions, headaches and soreness.

o Neck injuries with possible windshield involvement: body region is neck; contact code is windshield or it is a noncontact injury and the occupant has another injury which is due to windshield contact. Most of these are minor whiplash.

o Windshield ejection: the occupant's ejection portal was the windshield and the contact source for this injury was an object exterior to the vehicle.

NCSS is not a simple random sample but a stratified sample with 4 strata and unequal sampling proportions: 100, 25, 10 and 5 percent. Cases from the 4 strata are counted 1, 4, 10 or 20 times, respectively, in tabulations of NCSS data. As a result, the cell entries in some NCSS tables are much larger than would appear at first glance. Over 95 percent of the observed AIS $\geq$ 2 injuries in NCSS come from the 100 percent sampling stratum. Yet the remaining 5 percent, because of their higher weight factors, contribute disproportionately to sampling variances of NCSS statistics. For that reason, they have been excluded from the analyses of AIS $\geq$ 2 injuries in Chapters 4-7. Although somewhat artificial, the exclusion is indispensable for statistically meaningful results (see [18], pp. 146-149)).

The measure of injury risk used with NCSS is the number of injuries per 1000 crash-involved occupants. (Recall that each occupant may have up to 6 injuries.) Injury risk is calculated for the first 6 types of windshield-related injury defined above, plus for all seven types combined. It is defined at 2 severity levels:

- AIS $\geq$ 2 injuries from the 100 percent sampling stratum

- AIS 1 injuries from any sampling stratum

Two other measures of injury risk to be used with NCSS are defined at the occupant level and are based on the treatment received by the occupant. A person is "hospitalized as a consequence of windshield related injury" if that person is killed or hospitalized at least overnight and has a windshield related injury which

- is that person's most severe injury or
- has the same AIS as the most severe injury or
- has AIS $\geq$ 3.

If the occupant was hospitalized, had AIS 2 windshield injury, but had other injuries with AIS $\geq$ 3, this variable (hospitalized by windshield injury) is coded "unknown."

A person is "transported of a treatment facility as a consequence of windshield related injury" if that person is transported and has a windshield related injury which

- is that person's most severe injury or
- has the same AIS as the most severe injury or
- has AIS $\geq$ 2.

Variables of this type were used in earlier NHTSA evaluations [18], [21] and are especially suitable for use with the NCSS sampling plan.

NCSS investigators estimated a vehicle's Delta V using the CRASH computer program [26]. In the case of front seat occupants who were known to have contacted the windshield in a frontal crash, Delta V is used as a surrogate for the head-to-windshield contact velocity. The determination of whether the head penetrated the windshield is based on the NCSS variable V1GLDWND (windshield damage): codes 4, 6, 10 and 12 are the ones in which the windshield is broken (not just cracked) by occupant contact. Thus, the NCSS analyses of penetration velocities are limited to front seat occupants of frontally damaged cars, with known Delta V and known V1GLDWND and in which it is known that an occupant definitely contacted the windshield, as evidenced by windshield-contact injuries. This last criterion has the disadvantage of excluding occupants who contacted the windshield without injury but has the advantage of including only those cases with excellent documentation, where there is relatively the least doubt over what caused the windshield to crack or break.

NCSS investigators recorded the actual percentage of the windshield periphery that had become separated from the frame during a collision [39], p. 5-32. They also coded whether a person was ejected through the windshield portal [39], p. 6-13, and whether ejection was complete or partial. Cases of persons who merely penetrated the windshield with part of their heads were not normally coded as "partial ejectees." Instead, such coding meant that a significant proportion of the body came to rest outside the passenger compartment or the occupant contacted objects outside the compartment.

The following unweighted statistics provide an impression of the effective sample size of NCSS for the analyses of windshields:

	Last 5 MY before HPR	Last 5 MY before Adhesive Bonding
Nonminor windshield injuries	62	95
Nonminor windshield lacerations	38	40
Nonminor windshield concussions	8	26
Cars with more than 25% bond separation		72
Windshield ejections		11

NCSS can be expected to produce statistically meaningful results on the effect of HPR glazing on overall injury risk and lacerations and on the effect of bonding on windshield retention. But the results on concussions and windshield ejections will have a lot of sampling error.

3.3 New York State data (1974)

Automated New York State accident accident files were available for access by NHTSA for the calendar years 1974 and 1977. The latter were not used because they contain few pre-standard cars (the lifespan of the average auto is short because of the New York climate). The great advantage of these data is their use of the New York State Injury Coding System (NYSICS) which describes the body region, type and severity of a victim's principal injury.

New York codes the vehicle make but not the model; instead, it provides the VIN. A program for decoding VIN and determining the windshield mounting method of 1960-74 cars was prepared especially for this report.

Since New York does not code injury contact sources, the analyses consider head injury rates (from any source) of front-seat occupants in frontal crashes. The file identifies each occupant's seat position, making it easy to single out front seat occupants. "Frontal" crashes are defined according to the primary damage location and include cars with front or front-fender damage.

Only the most severe injury is coded for each occupant, which simplifies the problem of defining injury rates even though it causes an underestimate of the incidence of head injuries. The NYSICS body regions, head, eye, face and neck are all included among "head" injuries in this report. The NYSICS severity codes (unconscious, semiconscious, incoherent, shock and conscious) are descriptive terms for use by police rather than rigorous medical categories. They were not used for classifying the severity of injuries. Instead, the NYSICS lesion codes were used for classifying the severity as well as the type of injury. The codes are:

- o Amputation
- o Concussion
- o Internal
- o Minor bleeding
- o Severe bleeding
- o Burns
- o Fracture or dislocation
- o Contusion
- o Abrasion
- o Complaint of pain

Some very approximate correspondence between these codes and the categories of windshield related injuries established for NCSS are:

o "Severe bleeding" most nearly corresponds to AIS $\geq$ 2 facial or scalp lacerations, the type of injury for which HPR glazing should be most effective.

o "Fracture or dislocation" should be equivalent to the NCSS category of facial or skull fractures.

o "Minor bleeding" most nearly corresponds to AIS 1 facial or scalp lacerations.

o "Concussion" and "internal" most nearly corresponds to AIS ≥ 2 concussions on NCSS (nonminor blunt trauma).

o "Contusion" and "complaint of pain" are typical examples of AIS 1 blunt impact trauma.

Of course, it should be remembered that the New York data do not single out windshield contacts. Many of the head injuries, especially the nonlacerative ones, may have been due to other contact points.

Thus, the measures of injury risk used with New York data are the proportions of front-seat occupants in frontal crashes with severe bleeding, fracture, minor bleeding, concussion/internal, or contusion/complaint of pain, respectively.

New York codes whether or not an occupant was ejected but not the ejection portal. It contains too few ejection cases for a satisfactory analysis of the effect of adhesive bonding.

The following statistics provide an impression of the effective sample size of New York State data for the analyses of windshields:

	Last 4 MY before HPR	Last 4 MY before Adhesive Bonding	Volkswagens: Last 4 MY before Std. 212
Severe bleeding	693	529	87
Fractures	72	57	10
Concussions/internal	183	191	47
Ejections in frontal crashes (any portal)		208	52

New York State can be expected to produce statistically meaningful results on the effect of HPR glazing on severe bleeding and fractures (where relatively large effects are expected) and, perhaps, concussions (where no large effect is expected but a high degree of precision is unnecessary).

3.4 Texas data (1972-74)

Automated Texas accident files were available for access by NHTSA for the years 1972-74 and 1977. The latter were not used because all model years prior to 1967 were coded as "66" on that file. Texas does not provide any description of injuries other than the usual police severity codes K, A, B and C. K means "killed"; the other codes are described below. It also does not code uninjured passengers--thus, injury rates can be calculated for drivers only. Texas data are only useful in this study as a secondary source, with a very large sample size, to check the results from NCSS and New York.

Texas codes vehicle makes and models by enumerating all the well-known make/model names in alphabetical order. With these codes, it was straightforward to assign windshield mounting method, by model year, according to the information on Table 1-1; the only subtlety was a small group of names which corresponded to different size/market classes in different years (e.g., Pontiac Ventura).

Since Texas does not code injury locations contact sources, the analysis considers overall injury rates, by severity level, of drivers in frontal crashes (as stated above, front-seat passengers had to be excluded). "Frontal" crashes are those cars with frontal TAD [51] damage codes: FC, FD, FL, FR.

The severity codes for nonfatal injuries are defined on the Texas accident report form as follows:

A - serious visible injury as deep bleeding wound, distorted member, etc.

B - minor visible injury as bruises, abrasions, swelling, limping, etc.

C - no visible injury but complaint of pain or momentary unconsciousness

Whereas the three codes primarily act as a severity scale with A being most serious, they also seem to emphasize different types of injury. Level A, with its emphasis on deep bleeding wounds, is likely to include many facial lacerations, even if they are not too severe. Levels B and C appear to emphasize blunt impact trauma, which may even by nonminor ("momentary unconsciousness"). If HPR windshields, for example, are found to be primarily effective against A injuries it is probably because so many of them are lacerations.

The measures of injury risk used with Texas data in the analysis of HPR windshields are the proportions of drivers in frontal crashes with

- o A injury

- o B or C injury

Since 3 calendar years of Texas data are available, it is possible to perform regressions on the injury rates.

Texas does not code whether an occupant was ejected unless the occupant was killed. The data are not useful for analyzing the effect of adhesive bonding on ejection risk.

The following statistics provide an impression of the effective sample size of Texas data for the analyses of windshields.

	Last MY before HPR	Last 2 MY before HPR
Level A injuries	1362	2404
B or C injuries	4681	8212

Texas data contain a larger number of injuries than the other files, making it possible to detect smaller differences. On the other hand, the windshield injuries are buried among the injuries due to other contact surfaces, which will not be affected by Standards 205 or 212. Only a small change in aggregate injury risk can be expected for Standards 205 and 212. It may escape detection, even with these large samples.

3.5 Fatal Accident Reporting System (1975-82)

The Fatal Accident Reporting System (FARS) is a census of the Nation's fatal traffic accidents. FARS data were available for calendar years 1975-82. The file does not provide any description of injuries other than the usual police codes K (killed), A, B and C. Since FARS is limited to fatal accidents, it is impossible to calculate fatality rates per 100 (fatal or nonfatal) crash-involved occupants. Instead, fatality risk of occupants in frontal crashes has to be measured relative to a control group of occupant fatalities in nonfrontal crashes or relative to the number of vehicles on the road.

When "the number of vehicles on the road" is the denominator of the FARS statistic, it is expressed in millions of vehicle exposure years. Since FARS data were collected in 1975-82, the number of exposure years for a particular type of car (e.g., 1965 Chevrolet Impala) is the sum of the numbers of 1965 Impalas still on the road in 1975, 1976,...., 1982. These numbers are estimated by multiplying the number of 1965 Impalas originally sold by the proportion of vehicles that typically remains in service after 10, 11, ..., 17 years. The number of exposure years of "cars of the first MY with adhesive bonding" is the sum of the exposure years, thus calculated, of 1965 Impalas, 1966 Ford Fairlanes, 1967 AMC Ambassadors, etc. A detailed description of the calculation of exposure years for use with FARS data may be found on pp. 167-174 of NHTSA's evaluation of side door beams [21].

FARS has a well-designed 4 digit make/model code whereby each car's windshield mounting method could be determined without difficulties.

"Frontal" crashes are those whose principal impact location is 11, 12 or 1:00 on the clock scheme for damage reporting in FARS.

Since 8 calendar years of FARS data are available, the file is especially suitable for regression analyses.

FARS codes whether or not an occupant was ejected, but not the ejection portal. Thus, the effect of windshield installation method is analyzed by comparing the number of fatal ejectees to the number of persons who are killed and not ejected.

The following statistics provide an impression of the effective sample size of FARS data for the analyses of windshields.

	Last MY before HPR	Last MY before Adhesive Bonding	Last 4 MY before Adhesive Bonding	Volkswagens: Last 2 MY Before Std. 212
Frontal fatalities	2855			
Ejectees killed in frontal and rollover crashes		542	2090	306

Although 8 years of FARS contain a large number of fatalities, the likelihood of finding a significant change due to Standard 205 or 212 in the aggregate fatality data is small because only a few percent of all fatalities are due to windshield contact or ejection. A much better chance exists for finding a significant reduction in frontal and rollover ejections, since a substantial proportion of them are through the windshield portal. The 2090 frontal and rollover ejections on FARS should be enough to decide whether adhesive bonding reduces ejections.

3.6 Multidisciplinary Accident Investigation

The NCSS file, by itself, does not contain enough cases of occupants ejected through the windshield portal for a statistically meaningful analysis of the effects of windshield installation method. NHTSA's Multidisciplinary Accident Investigation (MDAI) file contains cases of 65 occupants who were ejected through the windshield portal of domestic or German passenger cars. When they are combined with the NCSS cases, it is possible to obtain statistically significant results on ejection. It is the only use made of MDAI data in this report.

One problem with the MDAI file is its lack of representativeness. The number of windshield ejectees per 1000 occupants on MDAI is surely higher than the rate in a nationally representative set of towaway crashes. But the relative difference of the windshield ejection rates with rubber gaskets and adhesive bonding on MDAI should not be as biased. When the relative difference is further controlled by comparing windshield ejectees to ejectees through other portals, there is no reason to believe that MDAI is biased at all.

3.7 Other vehicle modifications that could bias windshield analyses

Care must be exercized that injury reductions are not attributed to changes in windshield glazing and mounting when they are in fact due to other Federal Motor Vehicle Safety Standards or other vehicle modifications that are not Federally mandated. What are some of the vehicle modifications that could bias the analyses? How can the analyses be designed to identify and remove biases?

One factor that keeps all biases to a minimum is the overall analytic approach, which is described in the next two sections. The analyses primarily use data from the model years just before and after windshields were changed. Other vehicle modifications will not bias the results unless they more or less coincided with the windshield changeover. Another factor that helps is that the introduction of adhesive bonding was spread over a long time period. Other modifications, which are typically introduced over 1 or 2 model years, will only coincide with bonding for a fraction of the makes and models.

An important factor in regard to potential bias is the measure of injury risk used in the analyses. NCSS analyses are based on windshield-contact injury: other modifications will not bias the results unless they specifically affect windshield contact injuries. New York analyses are based on head injuries only; Texas and FARS, on all types of injury. Thus, NCSS analyses are the least susceptible to bias; Texas and FARS, the most.

The most important potential bias, which even affects NCSS, is the possibility of confusing the effects of HPR glazing and adhesive bonding with one another. The danger is avoided by performing four sets of New York analyses (similar to Fargo's approach with ACIR data--see Section 2.3.1):

- o Effect of HPR glazing in models that had rubber gaskets both before and after HPR
- o Effect of HPR in models that had adhesive bonding both before and after HPR
- o Effect of changing to adhesive bonding in pre-HPR models
- o Effect of changing to adhesive bonding in post-HPR models.

Unfortunately, the NCSS data set is too small to allow a similar approach. But the New York results provide assurances that Standard 212 does not significantly bias the analyses of Standard 205. The bias in the reverse direction may be substantial, necessitating the calculation of separate estimates for the effect of adhesive bonding in the "pre-HPR" and "post-HPR" environments.

Other modifications that could specifically affect windshield-contact injury rates are changes in the size and location of the instrument panel or in the rake angle of the windshield. But these biases ought to be minimal: Rieser and Michaels showed that a 45 degree change in windshield angle only had a moderate effect on glazing penetration velocity (see Section 2.1.2). Trosien and Patrick showed that complete removal of the instrument panel had little effect on windshield performance in sled tests (see Section 2.2.3). The much smaller changes in rake angles and instrument panels coinciding with vehicle restylings ought to have even less effect on windshield-contact injuries.

The most important modification that could bias aggregate injury rates and, to a lesser extent, head injury rates is the energy-absorbing steering assembly (Standards 203 and 204). It significantly reduced the injury risk of drivers in frontal crashes and was introduced in GM, Chrysler and AMC cars in 1967 and Fords in 1968 [18]. Some of the methods for avoiding this potential bias in the analysis of HPR glazing (introduced in 1966) are:

- o Use only the MY 1966 data for post-HPR injury rates, since those cars still had rigid steering assemblies.

- o Analyze drivers and right-front passengers separately, since the latter are not significantly affected by Standards 203 and 204.

- o Include "proportion of cars with energy-absorbing steering assemblies" as an independent variable in the regression analyses.

The first and third methods are used with FARS and Texas data; the second, with New York and FARS.

Padding of instrument panel tops and some other frontal interior surfaces was introduced during 1966-68 and is regulated by Standard 201 [8]. The year-by-year analysis approach (described in the next section) makes it possible to examine the potential biasing effect of padding in the New York analyses. It turns out to be minimal (see Sections 4.2 and 6.2).

Seat belt usage is unlikely to have biased the results because there was no appreciable change in belt usage by front-seat occupants in the years immediately surrounding the introduction of HPR windshields or adhesive bonding. In particular, the implementation of the starter interlock (MY 1974 only) took place at least two model years away from any model's transition from gaskets to adhesive bonding.

Standards 206 (Door Locks and Door Retention Components) and 214 (Side Door Strength) can influence the likelihood of occupant ejection. Since the FARS analysis of windshield installation methods compares the number of ejectees in frontal and rollover crashes to a "control" group of persons who are not ejected, those 2 standards could bias the analysis. Improved door locks and hinges meeting Standard 206 were installed in all domestic 1965 cars, the same year that adhesive bonding was introduced in full-sized GM and Fords. For that reason, all pre-1965 domestic cars are excluded from the FARS analysis of ejections. So are all model years of those make/models which received adhesive bonding in 1965 - the same year as the improved door locks (see Section 5.3 for more details). Volkswagens received even more important door lock improvements in 1968. Therefore, all pre-1968 (and, for balance, post-1971) Volkswagens are excluded from the FARS analysis of ejections. Standard 214 will not cause any significant biases because, except for the relatively low-volume Plymouth Barracuda and Dodge Challenger, it was implemented at least 2 model years away from the introduction date for adhesive bonding [21], p. 108.

3.8 Year-by-year analysis approach

Analyses are conducted, for example, on the following basic table of front-seat occupants involved in frontal crashes in New York or Texas:

Model year	Injured Occupants	Exposed Occupants
Last MY before HPR glazing	N_{11}	N_{12}
First MY with HPR glazing	N_{21}	N_{22}

The specific definition of "injured" depends on the data file and was defined earlier. It could be, for example, head injury with severe bleeding. The injury risk with pre-HPR glass is N_{11}/N_{12}. The risk with HPR glass is N_{21}/N_{22}. The reduction for HPR windshields is

$$= 1 - \frac{N_{21} \quad N_{12}}{N22 \quad N11}$$

As shown in the table, the basic analysis is limited to cars of the last year before HPR. The age difference between the two groups of cars is just one year. That minimizes potential sources of bias such as the effects of other vehicle modifications or the effects related to differences in vehicle age. On the other hand, it raises a possibility that a result could be due to an anomaly in vehicles of those particular model years or, more likely, a statistical mischance due to the limited sample size.

As a test, each basic analysis is repeated with an accident sample broadened to include cars of two model years before or after the windshield glazing changeover. Does the larger sample yield effectiveness results consistent with the basic analysis? As a further test, each analysis is again repeated to include cars of 3 model years before or after the changeover; then 4; then 5. Do the effectiveness estimates from the 5 analyses (hereinafter designated as ± 1 MY, ± MY, ± 3 MY, ± 4 MY, ± 5 MY) show any trend of, say, effectiveness increasing as the span of model years increases? If so, it could indicate that the observed accident reduction is, at least in part, due to vehicle age differences (because as the span of model years increases so does the average age differences of the pre- and post-standard cars). Likewise, the biasing effect of another safety standard (e.g., energy-absorbing steering assemblies) should become apparent when the span of model years is broadened to include the introduction year for that device (viz., 1967, which is the 2nd year after HPR).

The sequence of 5 effectiveness estimates gives an excellent intuitive feel for what is the best, unbiased value for effectiveness and how statistically reliable that value is. Of course, rigorous statistical tests of the 5 individual tables are also useful for estimating the precision of estimates.

The analyses for adhesive bonding proceed just like those for HPR glazing except that the basic table has rows labeled:

Last MY with rubber gaskets

First MY with adhesive bonding

Additional model years in either direction are supplied one-by-one.

The analysis of the effect of Standard 212 in Volkswagens has rows labelled:

MY 1969 (last year before Std. 212)

MY 1970 (first year after Std. 212)

The sample analysis used simple injury rates as a measure of risk. But the year-by-year approach works equally well with other measures of risk, such as

- o number of injuries per 1000 exposed persons (NCSS)
- o ratio of ejected to nonejected fatalities (FARS)
- o ejection fatalities per 1000 car years (FARS)
- o mean percent of windshield bond separation (NCSS)

The year-by-year approach was used extensively in NHTSA's evaluations of side door beams [21] and side marker lamps [20]. It proved very useful for isolating the effect of a safety standard when accident data are limited and there are many other factors affecting injury risk.

3.9 Regression analysis approach

3.9.1 "Injury" analyses

In preparation for a FARS regression analysis for HPPR, the fatal involvements of passenger cars are tabulated as follows:

Calendar Year (CY)	Model Year (MY)	Fatalities Frontal	Fatalities Nonfrontal
75	62	F(75,62)	N(75,62)
	63	F(75,63)	N(75,63)
	.	.	.
	.	.	.
	.	.	.
75	69	F(75,69)	N(75,69)
76	62	F(76,62)	N(76,62)
	.	.	.
	.	.	.
	.	.	.
76	69	F(76,69)	N(76,69)
77	.	.	.
.	.	.	.
.	.	.	.

where calendar year (CY) has range 75 - 82 and model year (MY) is allowed to range from 62 to 69.

Each line in the table furnishes a data point for the regression. The dependent variable is the logarithm of the ratio of frontal to nonfrontal fatalities:

$$\text{LOGODDS (CY, MY)} = \log \frac{F\ (CY,\ MY)}{N\ (CY,\ MY)}$$

If HPR is effective, frontal fatalities should decrease relative to nonfrontal ones and this variable should decrease for cars with HPR windshields (MY $\geq$ 66). The log of the odds ratio is selected as the dependent variable because it makes it exceptionally simple to derive an effectiveness estimate for HPR.

The independent variables are HPR, AGE, AGE^2, CY and STD203 where:

HPR = 0 if MY $\leq$ 64, i.e., the car was produced with a pre-HPR windshield

= 0.01 if MY = 65, where 1 percent of the fleet (Thunderbird) had HPR

= 1 if MY $\geq$ 66, i.e., the car had HPR glazing

AGE = CY - MY (vehicle age at the time of the crash)

AGE and AGE^2 are used to control for vehicle-age related trends in the fatality rates. CY is used as a categorical variable in the regression and control for year-to-year differences in FARS.

Finally, if energy-absorbing steering assemblies are suspected of biasing the injury rates, their bias can be removed by simply adding one more independent variable:

$$STD203 = 0 \text{ if } MY \leq 66$$
$$= 0.71 \text{ if } MY = 67$$
$$= 1 \text{ if } MY \geq 68$$

A weighted regression is run. Each (CY, MY) data point is weighted by the total number of fatalities in that calendar year and model year: F (CY, MY) + N (CY, MY). The runs were made by the General Linear Model procedure of the Statistical Analysis System(SAS) which allows weighted regressions with mixed linear and categorical variables [46].

The regression equation is

$$\log \frac{F}{N} = a_o + a_1 \, HPR + a_2 \, AGE + \ldots$$

When a car's windshield is pre-HPR, the frontal fatality risk is

$$F_o = N \exp (a_o + a_2 \, AGE + \ldots)$$

because HPR = 0. If that same car had HPR glazing, the risk would have been

$$F_1 = N \exp (a_o + a_1 + a_2 \, AGE + \ldots)$$

because HPR = 1. Therefore, the effectiveness estimate for HPR is

$$E = 1 - \frac{F_1}{F_0} = 1 - \exp(a_1)$$

for any car, where a_1 is the regression coefficient assigned to HPR by the model.

For regressions on Texas data, a linear model is more satisfactory because the injury rates vary considerably as a function of vehicle age [22], pp. 42-43. Here, the range of calendar years CY is 72-74. Since the measure of risk is the simple injury rate, the dependent variable is

$$\text{Rate} = \frac{\text{Injured occupants (CY, MY)}}{\text{Crash-involved occupants (CY, MY)}}$$

and the regression weight factor is the number of crash-involved occupants.

The regression equation is Rate = $a_o + a_1$ HPR + a_2 AGE .... Set the values of all independent variables other than HPR to their mean value m_i in the current automobile population (e.g., average AGE = 7). Then the effectiveness of HPR is approximately

$$E = 1 - \frac{a_o + a_1 + a_2 m_2 + a_3 m_3 + \ldots}{a_o \qquad + a_2 m_2 + a_3 m_3 + \ldots}$$

Texas data are also used for regression analyses of the effect of adhesive bonding on injury rates. Here, the dependent variable is

$$\text{Rate (CY, YT)} = \frac{\text{Injured occupants (CY, YT)}}{\text{Crash-involved occ. (CY, YT)}}$$

where CY, the calendar year, has range 72-74. YT is the number of model years before/after the transition year to adhesive bonding and is limited to a range of -4 to +3. For example, Rate (72, 1) is the injury rate, in 1972 data, for cars built one model year after the transition year (1966 Chevrolet Impalas, since their transition year was 1965; 1967 Ford Fairlanes; 1972 Plymouth Satellites, etc.). The regression equation is

$$\begin{aligned} \text{Rate} = a_o &+ a_1 \text{ ADHESIVE} + a_2 \text{ AGE} + a_3 \text{ AGE}^2 \\ &+ a_4 \text{ STD203} + a_5 \text{ HPR} + a_6 \text{ CY72} + a_7 \text{ CY73} \end{aligned}$$

and the regression weight factor is the number of crash-involved occupants. The values of ADHESIVE, STD203 and HPR depend on YT and are calculated from the model year distribution in Texas accident data of the clss of cars with a particular value of YT:

YT	ADHESIVE	STD203	HPR
-4	0	0.12	0.13
-3	0	0.15	0.44
-2	0	0.14	0.34
-1	0	0.28	0.29
-0	1	0.28	0.38
1	1	0.24	1
2	1	0.84	1
3	1	1	1

Effectiveness is calculated from the regression equation by the same method as in the preceding Texas model.

FARS and Texas data were successfully analyzed by similar regressions in NHTSA's evaluations of head restraints [19], side door beams [21], braking improvements [22] and side marker lamps [20].

3.9.2 "Engineering" analyses

Logistic regression is used for the analyses of windshield penetration velocity of Chapters 4 and 6. The independent variables are Delta V, HPR and ADHESIVE (the latter is omitted in Chapter 4). Delta V is partitioned into 5 mph intervals: 1-4, 5-9, 10-14, ..., 35-39 and 40+.

Front-seat occupants who contacted the windshield in a frontal crash are tabulated by penetration/nonpenetration, Delta V interval, HPR and ADHESIVE. The regression equation is

$$\log \frac{\text{n of penetrators}}{\text{n of nonpenetrators}} = a_o + a_1 \text{ DV} + a_2 \text{ HPR} + a_3 \text{ ADHESIVE}$$

which is equivalent to

$$P \text{ (penetration)} = \frac{\exp (a_o + a_1 \text{ HPR} + a_2 \text{ HPR} + a_3 \text{ ADHESIVE})}{1 + \exp (a_o + a_1 \text{ DV} + a_2 \text{ HPR} + a_3 \text{ ADHESIVE})}$$

which is the S-shaped dose-response curve. Each data point in the regression is weighted by the number of cases on which it is based. The PD_{50}, the "dose" of Delta V at which half the occupants will penetrate the windshield, is $-a_o/a_1$ for pre-HPR windshields with rubber gaskets, $-(a_o + a_2)/a_1$ for HPR windshields with rubber gaskets, $-(a_o + a_3)/a_1$ for adhesively bonded pre-HPR windshields and $-(a_o + a_2 + a_3)/a_1$ for bonded HPR windshields.

Logistic regression has been used for many years in medical research and was first used by Klimko and Friedman to study the effect of crash severity on injury severity [24].

Logistic regression is similarly used for estimating the likelihood of severe windshield bond separation as a function of Delta V (Section 5.1.5). Here, vehicles in frontal crashes on NCSS are tabulated by amount of bond separation (up to 50 percent, more than 50 percent), windshield installation method and Delta V interval. The dependent variable is

$$\log = \frac{\text{N with more than 50\% bond sep.}}{\text{N with less than 50\% bond sep.}}$$

and the regression equation is similar to the preceding case.

Weighted linear regression is used in Section 5.1.4 to estimate the expected amount of bond separation as a function of Delta V. Each NCSS case of a vehicle involved in a frontal crash is a data point in the regression, weighted by its inverse sampling fraction. The dependent variable is simply the percentage of bond separation for that vehicle. The independent variables are Delta V, Delta V squared, the windshield installation method, and the vehicle's age at the time of the crash.

CHAPTER 4

THE EFFECT OF THE HIGH PENETRATION RESISTANT WINDSHIELD ON INJURY RISK

Analyses of NCSS and New York State data show that High Penetration Resistant (HPR) windshields are highly effective in mitigating nonminor lacerations, eye, nose and mouth injuries and facial fractures, eliminating 50 to 80 percent of these injuries. They may also be effective against minor lacerations, but to a much smaller extent. They do not appear to have any influence on concussions or minor blunt impact trauma. Analyses of FARS do not show a significant effect on fatalities. The NCSS data are entirely consistent with laboratory studies; in both cases HPR glazing approximately doubled the velocity needed for the head to penetrate the windshield (a phenomenon associated with facial lacerations and fractures) but had little or no effect on blunt impact forces.

The procedures and definitions for this chapter's analyses of NCSS, New York, Texas and FARS data were set forth in Chapter 3.

4.1 NCSS data on windshield contact injuries

Because NCSS investigators were required to code the specific type of injury and its contact source, it is possible to calculate the number of windshield contact injuries per 1000 crash-involved occupants, by injury type (see Section 3.2).

4.1.1 Serious lacerations and other injuries associated with windshield penetration

Table 4-1 shows that HPR windshields are exceedingly effective in preventing nonminor (AIS $\geq$ 2) lacerations of the face and head. It is the type of injury most characteristically associated with crashes where an occupant's head penetrates the windshield's plastic interlayer (see Section 1.3). There were 1858 occupants in cars of the last model year before HPR windshields (generally 1965); there were 22 nonminor lacerations attributed to windshield contact among these persons, which is an injury rate of 11.84 per 1000 persons. There were 3087 occupants of cars of the first model year with HPR; only 5 nonminor lacerations were attributed to windshield contact among them, an injury rate of 1.62 per 1000 persons. Thus, the injury risk was 86 percent lower in the first year of HPR windshields than in the last year without them. When the NCSS sample is expanded to include the second model year before and after the transition to HPR, the injury reduction is just slightly lower: 82 percent. With data from 3 model years, the reduction drops to 73 percent and stabilizes there, since it is 72 and 74 percent in the $\pm$4 and $\pm$5 year comparisons. The sequence of 5 effectiveness estimates--86, 82, 73, 72, 74--does not show a vehicle-age related trend (because such a trend would typically have higher effectiveness over the wider age ranges--see Section 3.7). Rather, the first two numbers are probably a bit overstated as a result of sampling error (they are based on the smallest samples). The true reduction for HPR windshields would appear to be about 75 percent. No other safety device evaluated by NHTSA to date (May 1984) has come anywhere near as close to eliminating the type of injury it was specifically designed to mitigate.

TABLE 4-1

SERIOUS LACERATIONS* DUE TO WINDSHIELD CONTACT, BY TYPE OF GLAZING (NCSS)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Reduction for HPR (%)
Last w/o HPR	22	1858	11.84	
First with HPR	5	3087	1.62	86
Last 2 w/o HPR	34	3401	10.00	
First 2 with HPR	13	7039	1.85	82
Last 3 w/o HPR	36	4163	8.65	
First 3 with HPR	28	12,057	2.32	73
Last 4 w/o HPR	38	4677	8.12	
First 4 with HPR	44	19,111	2.30	72
Last 5 w/o HPR	38	4958	7.66	
First 5 with HPR	52	26,110	1.99	74

*AIS $\geq$ 2, lacerations or avulsions of the face or head excluding brain or spinal cord

Distressing injuries of the eyes, nose and mouth, such as ocular avulsions, compound nasal fractures and deep lacerations of the lips or tongue were associated with the head rebounding toward the car interior after penetrating the windshield (see Section 1.3). Table 4-2 shows that HPR glazing dramatically reduced AIS $\geq$ 2 injuries to those organs. The sequence of 5 effectiveness estimates (for 1-5 model years before/after HPR) is 86, 84, 72, 73, 72 percent, which is almost identical to the sequence for nonminor lacerations. It suggests that actual effectiveness is on the order of 70-75 percent.

Many facial fractures are believed to be the result of contacting the hard edges of a hole punched through the windshield by the occupant's head. Table 4-3 confirms that hypothesis, indicating that HPR windshields, which raise the penetration velocity without significantly affecting blunt impact forces of unbroken windshields, have reduced facial fractures. The sequence of effectiveness estimates--25, 31, 31, 48, 56 percent--leaves some ambiguity about how effective they are. Since the fractures are less common than lacerations, Table 4-3 is subject to more sampling error than Table 4-1. The monotone increase in the effectiveness sequence could indicate an age trend or just "bad luck" in the first year with HPR. NCSS data would appear consistent with an effectiveness in the 20 to 60 percent range; New York State data will also need to be analyzed to narrow that range.

4.1.2 Minor lacerations

When impact speeds are lower and the windshield cracks without penetration or tearing of the plastic interlayer, occupants may suffer minor lacerations from the cracked glass. HPR glazing cannot be expected to have as large an effect on minor lacerations as on serious

TABLE 4-2

NONMINOR INJURIES OF THE EYES, NOSE OR MOUTH DUE TO WINDSHIELD CONTACT, BY TYPE OF GLAZING (NCSS)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Reduction for HPR (%)
Last w/o HPR	13	1858	7.00	
First with HPR	3	3087	0.97	86
Last 2 w/o HPR	15	3401	4.41	
First 2 with HPR	5	7039	0.71	84
Last 3 w/o HPR	16	4163	3.84	
First 3 with HPR	13	12,057	1.08	72
Last 4 w/o HPR	18	4677	3.85	
First 4 with HPR	20	19,111	1.05	73
Last 5 w/o HPR	18	4958	3.63	
First 5 with HPR	27	26,110	1.03	72

TABLE 4-3

NONMINOR FACIAL FRACTURES DUE TO WINDSHIELD CONTACT, BY TYPE OF GLAZING (NCSS)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Reduction for HPR (%)
Last w/o HPR	4	1858	2.15	
First with HPR	5	3087	1.61	25
Last 2 w/o HPR	7	3401	2.06	
First 2 with HPR	10	7039	1.42	31
Last 3 w/o HPR	7	4163	1.68	
First 3 with HPR	14	12,057	1.16	31
Last 4 w/o HPR	9	4677	1.92	
First 4 with HPR	19	19,111	0.99	48
Last 5 w/o HPR	9	4958	1.82	
First 5 with HPR	21	26,110	0.80	56

ones, since the minor ones usually do not involve penetration. But there might be some benefit because HPR causes the glass to crack into finer pieces. Table 4-4 shows that, indeed, the effect of HPR glass on minor injuries is much smaller. The sequence of effectiveness estimates--51, 33, 35, 35 and 38 percent--suggest an actual value of about 35 percent (as opposed to 75 percent for the serious lacerations). Nevertheless, 35 percent is a substantial reduction--more than would be intuitively expected. New York State data also need to be analyzed to see if they confirm the NCSS result. In particular, the injury rates in Table 4-4 contain a lot more sampling error than is suggested by the counts on which they are based: many minor injuries occur in the 25 percent or 10 percent sampling strata of NCSS. Thus, the injury counts in Table 4-4 are really based on much smaller numbers of cases.

4.1.3 Blunt impact trauma

Concussions, contusions and other blunt impact trauma are thought to occur mainly before the head penetrates the windshield or in nonpenetration crashes, i.e., as a result of forces exerted during initial contact with the glass or while the head plows into the plastic without tearing it. Laboratory tests had shown the forces to be about the same in HPR and pre-HPR glazing (see Section 2.1).

Table 4-5, on the other hand, shows a possible increase in concussions and other nonminor brain injuries for HPR windshields. The sequence of effectiveness estimates is -8, -5, -21, -40 and -33 percent. Concussions due to windshield contact are rare events: there are only 8 in all the pre-HPR cars. Thus, the results in Table 4-5 are subject to a lot of sampling error and cannot be accepted at face value unless confirmed by New York State data.

TABLE 4-4

MINOR LACERATIONS DUE TO WINDSHIELD CONTACT,
BY TYPE OF GLAZING (NCSS)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Reduction for HPR (%)
Last w/o HPR	75	1858	41.98	
First with HPR	64	3087	20.73	51
Last 2 w/o HPR	120	3401	35.28	
First 2 with HPR	167	7039	23.73	33
Last 3 w/o HPR	132	4163	31.71	
First 3 with HPR	247	12,057	20.48	35
Last 4 w/o HPR	151	4677	32.29	
First 4 with HPR	398	19,111	20.83	35
Last 5 w/o HPR	166	4958	33.48	
First 5 with HPR	542	26,110	20.76	38

TABLE 4-5

CONCUSSIONS* DUE TO WINDSHIELD CONTACT,
BY TYPE OF GLAZING (NCSS)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Reduction for HPR (%)
Last w/o HPR	5	1858	2.69	
First with HPR	9	3087	2.92	-8
Last 2 w/o HPR	6	3401	1.76	
First 2 with HPR	13	7039	1.85	-5
Last 3 w/o HPR	6	4163	1.44	
First 3 with HPR	21	12,057	1.74	-21
Last 4 w/o HPR	7	4677	1.50	
First 4 with HPR	40	19,111	2.09	-40
Last 5 w/o HPR	8	4958	1.61	
First 5 with HPR	56	26,110	2.14	-33

*Closed-head brain injuries with AIS $\geq$ 2

NCSS also does not offer clear-cut results on minor blunt impact trauma such as headaches and contusions. Table 4-6 presents a sequence of effectiveness estimates that starts out positively but seems to converge on zero: 49, 31, 28, 19 and 4 percent. The very positive results for the narrower samples may be due to sampling error--the injury counts shown in Table 4-6 are inflated by the case weighting factors and are based on much smaller actual numbers of cases. The results will have to be checked by analyzing New York State data.

Whiplash (noncontact neck injury) could occur if the occupant's head is stopped by the windshield while the torso is still moving forward, extending the neck. Table 4-7 examines the incidence of whiplash injury accompanied by head contacts with the windshield. The sequence of effectiveness estimates, which is based on small numbers of whiplash cases, is 29, 19, 18, 7 and -20 percent. It does not indicate any clear-cut effect for HPR windshields.

4.1.4 Overall reduction of windshield-related injuries

What is the net effectiveness of HPR glazing when all categories of windshield-related injuries--lacerations, blunt impact trauma, ejections through the windshield, induced whiplash--are combined? Two measures of risk were defined in Section 3.2: (i) the number of persons hospitalized (or transported) per 1000 crash-involved persons, (ii) the number of individual injuries per 1000 crash-involved persons.

Table 4-8 shows the number of persons hospitalized (for at least one night) as a consequence of windshield-related injury. HPR glass clearly reduced the likelihood of injuries requiring hospitalization. The sequence of effectiveness estimates--33, 37, 35, 39 and 39 percent--suggests a reduction in hospitalizations on the order of 35

TABLE 4-6

MINOR BLUNT-IMPACT HEAD INJURIES* DUE TO WINDSHIELD CONTACT, BY TYPE OF GLAZING (NCSS)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Reduction for HPR (%)
Last w/o HPR	75	1858	40.37	
First with HPR	63	3087	20.41	49
Last 2 w/o HPR	108	3401	31.76	
First 2 with HPR	154	7039	21.88	31
Last 3 w/o HPR	110	4163	26.42	
First 3 with HPR	228	12,057	18.91	28
Last 4 w/o HPR	114	4677	24.37	
First 4 with HPR	377	19,111	19.73	19
Last 5 w/o HPR	118	4958	23.80	
First 5 with HPR	599	26,110	22.94	4

*Headaches, contusions

TABLE 4-7

WHIPLASH INJURIES OF PERSONS WHOSE HEAD HIT THE WINDSHIELD, BY TYPE OF GLAZING (NCSS)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Reduction for HPR (%)
Last w/o HPR	16	1858	8.61	
First with HPR	19	3087	6.15	29
Last 2 w/o HPR	19	3401	5.59	
First 2 with HPR	32	7039	4.55	19
Last 3 w/o HPR	19	4163	4.56	
First 3 with HPR	45	12,057	3.73	18
Last 4 w/o HPR	22	4677	4.70	
First 4 with HPR	84	19,111	4.40	7
Last 5 w/o HPR	23	4958	4.64	
First 5 with HPR	145	26,110	5.55	-20

TABLE 4-8

PERSONS HOSPITALIZED BY WINDSHIELD-RELATED*
INJURIES, BY TYPE OF GLAZING (NCSS)

Model Years	n of Persons Hospitalized	N of Persons Involved	Hospitalizations per 1000 Persons	Reduction for HPR (%)
Last w/o HPR	28	1856	15.09	
First with HPR	31	3083	10.06	33
Last 2 w/o HPR	40	3396	11.78	
First 2 with HPR	52	7031	7.40	37
Last 3 w/o HPR	41	4156	9.87	
First 3 with HPR	80	12,496	6.40	35
Last 4 w/o HPR	46	4669	9.85	
First 4 with HPR	114	19,097	5.97	39
Last 5 w/o HPR	47	4950	9.49	
First 5 with HPR	152	26,092	5.82	39

*Injuries due to windshield contact, windshield ejection or secondary neck injury

percent. Table 4-9 counts the numbers of individual nonminor (AIS ≥ 2) injuries per 1000 occupants. HPR glazing was even more effective by that measure. The sequence of estimates--65, 63, 57, 53 and 54 percent--suggest a reduction on the order of 55 percent. The increase could reflect the fact that HPR glazing reduced the number of injuries per person or that some of the nonminor lacerations eliminated by HPR would not have required hospitalization.

Tables 4-10 and 4-11 provide analogous results for less severe injuries. Table 4-10 shows the number of persons transported to a treatment facility (but not necessarily hospitalized) as a consequence of windshield-related injury. The sequence of effectiveness estimates--38, 29, 35, 29 and 25 percent--suggest a reduction on the order of 25-30 percent. Table 4-11 indicates a reduction of perhaps 15-25 percent in the number of individual minor injuries; the sequence of effectiveness estimates is 42, 30, 29, 23 and 16 percent.

These tables show that whereas HPR windshields have been exceedingly successful in mitigating serious lacerations, there are still many windshield-related injuries occurring with HPR.

4.1.5 Serious facial lacerations due to any contact source--results analogous to New York State data

Table 4-12 presents an analysis of NCSS whose results are directly comparable to New York State data: nonminor facial lacerations (due to any contact source) of front-seat occupants involved in frontal crashes. The sequence of effectiveness estimates--67, 61, 58, 57 and 61 percent--suggest that HPR glazing eliminates about 60 percent of all

TABLE 4-9

NONMINOR (AIS $\geq$ 2) WINDSHIELD-RELATED*
INJURIES, BY TYPE OF GLAZING (NCSS)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Reduction for HPR (%)
Last w/o HPR	36	1858	19.38	
First with HPR	21	3087	6.80	65
Last 2 w/o HPR	54	3401	15.88	
First 2 with HPR	41	7039	5.82	63
Last 3 w/o HPR	56	4163	13.45	
First 3 with HPR	73	12,507	5.83	57
Last 4 w/o HPR	61	4677	13.04	
First 4 with HPR	116	19,111	6.07	53
Last 5 w/o HPR	62	4958	12.51	
First 5 with HPR	150	26,110	5.74	54

*Injuries due to windshield contact, windshield ejection or secondary neck injury

TABLE 4-10

PERSONS TRANSPORTED TO EMERGENCY ROOMS FOR TREATMENT OF WINDSHIELD-RELATED* INJURIES, BY TYPE OF GLAZING (NCSS)

Model Years	n of Persons Transported	N of Persons Involved	Casualties per 1000 Persons	Reduction for HPR (%)
Last w/o HPR	111	1858	59.74	
First with HPR	114	3087	36.93	38
Last 2 w/o HPR	173	3401	50.87	
First 2 with HPR	256	7039	36.36	29
Last 3 w/o HPR	191	4163	45.88	
First 3 with HPR	371	12,507	29.66	35
Last 4 w/o HPR	208	4677	44.47	
First 4 with HPR	600	19,111	31.40	29
Last 5 w/o HPR	218	4958	43.97	
First 5 with HPR	862	26,110	33.01	25

*Injuries due to windshield contact, windshield ejection, or secondary neck injury

TABLE 4-11

MINOR WINDSHIELD-RELATED* INJURIES, BY
TYPE OF GLAZING (NCSS)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Reduction for HPR (%)
Last w/o HPR	176	1858	94.73	
First with HPR	169	3087	54.75	42
Last 2 w/o HPR	260	3401	76.45	
First 2 with HPR	378	7039	53.70	30
Last 3 w/o HPR	276	4163	66.30	
First 3 with HPR	586	12,507	46.85	29
Last 4 w/o HPR	303	4677	64.79	
First 4 with HPR	959	19,111	50.18	23
Last 5 w/o HPR	323	4958	65.15	
First 5 with HPR	1433	26,110	54.88	16

*Injuries due to windshield contact, windshield ejection or secondary neck injury

TABLE 4-12

SERIOUS FACIAL LACERATIONS* DUE TO ANY CONTACT SOURCE, FRONT SEAT OCCUPANTS IN FRONTAL CRASHES, BY TYPE OF GLAZING (NCSS)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Reduction for HPR (%)
Last w/o HPR	29	946	30.66	
First with HPR	15	1501	9.99	67
Last 2 w/o HPR	49	1897	25.83	
First 2 with HPR	35	3487	10.04	61
Last 3 w/o HPR	54	2256	23.94	
First 3 with HPR	62	6231	9.95	58
Last 4 w/o HPR	59	2510	23.51	
First 4 with HPR	94	9278	10.13	57
Last 5 w/o HPR	59	2670	22.10	
First 5 with HPR	109	12,490	8.73	61

*AIS $\geq$ 2, lacerations or avulsions of the face or head excluding brain or spinal cord serious lacerations from all sources combined. In other words, approximately 80 percent of all serious facial lacerations in pre-HPR cars were due to windshield contacts; HPR eliminated 75 percent of the windshield contact lacerations and .75 x .8 = 60 percent of all lacerations.

4.2 NCSS data on windshield penetration in accidents

4.2.1 Windshield penetration velocities

Table 4-13 shows that the HPR windshields approximately doubled the impact velocity needed for an occupant's head to penetrate the windshield. As explained in Section 3.2, the analysis is based on NCSS accident data and uses "windshield broken by occupant contact" as a surrogate for "penetration" and the vehicle's Delta V as a surrogate for the head-windshield impact velocity. It is based on front-seat occupants in frontal crashes who were known to have been injured by a windshield contact. In this section, the entire NCSS file is used without restriction of the range of vehicle age--in order to maximize sample size and because Delta V acts as a control variable, reducing the potential bias of vehicle age effects. About half of the pre-HPR windshields that are struck by occupant's heads in crashes with Delta V in the teens are penetrated; almost all of those with Delta V in the 20's. By contrast, fewer than 10 percent of HPR windshields are penetrated at speeds in the teens, as are less than a quarter of those struck at speeds in the 20's.

Over the full range of highway accident speeds, HPR windshields were 78 percent less likely to be penetrated by an occupant's head than pre-HPR glass.

TABLE 4-13

WINDSHIELD PENETRATION BY TYPE OF GLAZING AND DELTA V, FRONT-SEAT OCCUPANTS IN FRONTAL CRASHES WITH WINDSHIELD CONTACT INJURIES (NCSS)

Delta V	N of Persons	Percent Penetrating the Windshield
	PRE-HPR WINDSHIELDS	
1-4	--	--
5-9	30	40
10-14	41	54
15-19	35	43
20-24	20	85
25-29	12	83
30-34	9	67*
35-39	4	0*
40+	1	0*
ALL SPEEDS	152	54
	HPR WINDSHIELDS	
1-4	28	0
5-9	321	0
10-14	664	6
15-19	625	8
20-24	355	24
25-29	168	20
30-34	124	27
35-39	33	42
40+	40	68
ALL SPEEDS	2358	12

*Windshields apparently broke before being contacted by occupants.

When the table entries are entered into a logistic regression (as described in Section 3.9.2 the following equation is obtained:

$$P\ (\text{penetration}) = \frac{\exp\ (-2.98 + 0.211\ DV - 3.60\ HPR)}{1 + \exp\ (-2.98 + 0.211\ DV - 3.60\ HPR)}$$

where df = 11 and R^2 = .62. This is a statistically significant reduction in penetration for HPR ($F = 3.75$; df = 1, 11; $P < .05$). The PD_{50} - the Delta V at which a pre-HPR windshield has 50 percent chance of being penetrated - is 14 mph. The PD_{50} for HPR windshields is 31 mph - slightly more than double. The regression lines and the data points they are based on are graphed in Figure 4-1.

These results are amazingly close to Rieser and Michaels' drop tests with 22 pound headforms (14 mph penetration velocity with pre-HPR and 28 mph with HPR glass) and Patrick and Daniel's cadaver tests--see Section 2.1--all the more so, considering the uncontrolled conditions of the highway accidents, the opportunity for discrepancies between the vehicle's Delta V and the head-windshield contact velocity, and the possibility of errors in the estimates of Delta V.

4.2.2 Windshield penetration and the risk of serious lacerations

Table 4-13 indicated that HPR windshields reduced the overall incidence of penetration in highway crashes by 78 percent. To what extent is the HPR windshield's reduction of serious lacerations (about 75 percent according to Section 4.1.1) directly attributable to the increase in the velocity needed to penetrate the windshield?

FIGURE 4-1: LIKELIHOOD OF WINDSHIELD PENETRATION BY TYPE OF GLAZING AND DELTA V, FRONT-SEAT OCCUPANTS IN FRONTAL CRASHES WITH WINDSHIELD CONTACT INJURIES (NCSS PROBABILITIES AND LOGISTIC REGRESSION CURVES)

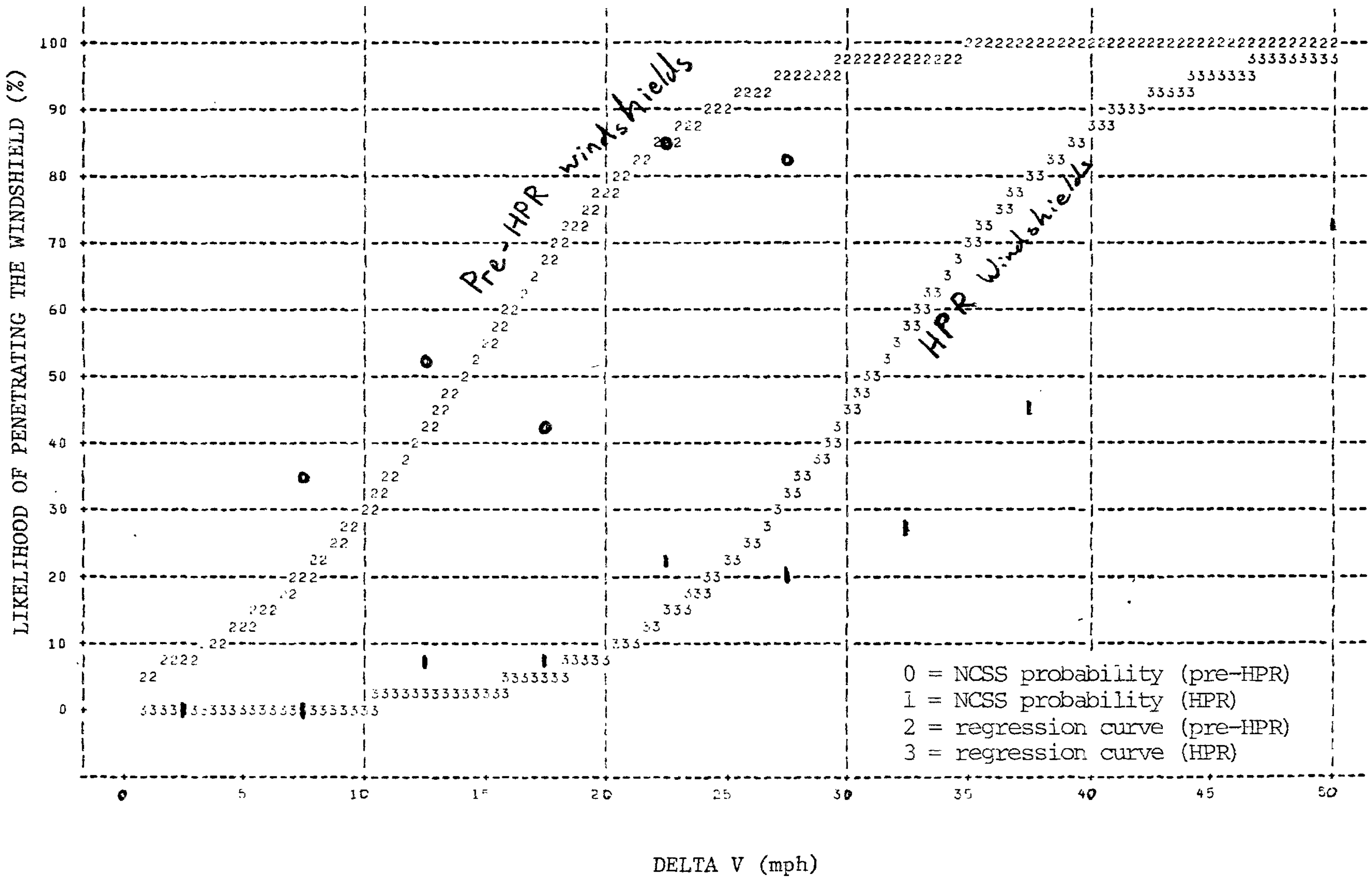


Table 4-14 shows the percentage of persons contacting the windshield who were seriously lacerated--as a function of Delta V, type of windshield (HPR versus pre-HPR) and whether or not the occupant penetrated the interlayer. The table pushes to the limit the number of cells into which the NCSS sample can be subdivided and the injury rates are subject to a good deal of sampling error. Certain trends, nevertheless, are fairly evident: penetration increases the risk of serious lacerations by a factor of 3. Within each of 4 groups of occupants (pre-HPR with no penetration, pre-HPR with penetration, etc.), Delta V only seems to have, at most, a weak relationship with laceration risk--certainly nothing like the relationship between Delta V and most forms of blunt impact trauma. The influence of Delta V is indirect--higher Delta V increases the risk of penetration which in turn raises injury risk. Thus, clearly, the principal reason that HPR glazing reduces serious lacerations is that it reduces the likelihood of penetration, the most influential factor, by 78 percent. Table 4-14 also suggests that, to a lesser extent, HPR glass may have had an additional benefit, independent of reducing penetration. The overall laceration rate for nonpenetrators is 6 percent with HPR, 9 percent with pre-HPR; for penetrators the rates are 19 and 26 percent, respectively. The reduction is probably due to the fact that HPR glass cracks and breaks into smaller (less dangerous) pieces than pre-HPR glass, regardless of whether penetration occurs, due to the looser glass-plastic bond in HPR.

TABLE 4-14

SERIOUS LACERATIONS BY TYPE OF GLAZING, PENETRATION, AND DELTA V, FRONT-SEAT OCCUPANTS INJURED BY WINDSHIELD CONTACT IN FRONTAL CRASHES (NCSS)

Delta V	Windshield Contacted But Not Penetrated		Windshield Penetrated	
	N	% with Serious Lacerations	N	% with Serious Lacerations
PRE-HPR WINDSHIELDS				
1-19	57	11	49	27
20-34	8	0	33	24
1-34*	65	9	82	26
HPR WINDSHIELDS				
1-9	349	2	--	--
10-19	1197	6	92	25
20-29	370	9	118	14
30-39	110	10	47	23
40+	13	8	27	15
ALL SPEEDS	2074	6	284	19

*Cases over 34 mph excluded because most windshields shattered prior to occupant contact

Table 4-15 compares the roles played by windshield penetration in the occupants' injury profiles in pre- and post-HPR cars. The table is based on domestic cars built within 5 years of the HPR introduction date, includes cases with unknown Delta V and counts injured persons, not individual injuries. Whereas HPR glazing reduced the likelihood of serious windshield-contact lacerations by 68 percent overall, it was primarily successful against penetration-related injuries. The likelihood of penetration-related serious lacerations was cut by 86 percent--Standard 205 was almost completely successful in achieving its most specific objective. But HPR had little net effect on lacerations that were not associated with penetrated windshields.

To put it another way: 78 percent of the serious lacerations in pre-HPR cars were associated with windshield penetration. The first priority before 1966 was to increase the penetration velocity. HPR accomplished that goal. As a result, only 34 percent of serious lacerations today are associated with penetrated windshields.

4.3 New York State data on head injuries

Because it has a much larger sample size than NCSS, the New York State file is useful for resolving most of the uncertainties of the NCSS analyses. While the data do not specify the injury contact source, they do indicate the body region injured and the type of lesion (see Section 3.3).

TABLE 4-15

SERIOUS LACERATIONS DUE TO WINDSHIELD CONTACT BY TYPE OF GLAZING AND PENETRATION, ALL FRONT-SEAT OCCUPANTS IN FRONTAL CRASHES, DOMESTIC CARS OF MODEL YEARS 1961-70 (NCSS)

	Pre-HPR	HPR	Reduction for HPR (%)
N of front seat occupants in frontal crashes	2670	12,490	
n with serious lacerations due to windshield	27	41	
Injury rate (per 1000 crash-involved occupants)	10.11	3.28	68
WINDSHIELD NOT PENETRATED			
n with serious lacerations	6	27	
Injury rate	2.25	2.16	4
WINDSHIELD PENETRATED			
n with serious lacerations	21	14	
Injury rate	7.87	1.12	86
Percent of serious lacerations involving a penetrated windshield	78	34	

4.3.1 Serious lacerations and other injuries associated with windshield penetration

Table 4-16 confirms the NCSS findings that HPR windshields are highly effective in preventing serious lacerations of the face and head. The injury criterion used in Table 4-16 is police-reported "severe bleeding" of the face or head (contact source unspecified) for front-seat occupants in frontal crashes. The observed effectiveness values when cars of the first 1, 2, 3 or 4 years with HPR, respectively, are compared to cars of the last 1, 2, 3 or 4 years before HPR are 33, 42, 46 and 52 percent. The latter two values in the sequence are quite comparable to the 55-60 percent reduction of AIS $\geq$ 2 facial lacerations (any contact source) found in NCSS--see Table 4-12. On the other hand, the diminished effectiveness in the first year of HPR--33 percent--and the monotone increasing trend of the sequence of estimates raise questions as to what is the "best" value for injury reduction.

The first question is if the diminished first-year showing and the trend could be due to chance alone. But the numbers of injuries in Table 4-16 (348 serious lacerations in the last model year before HPR and 278 in the first year with HPR) are more than 10 times as large as those in NCSS. The injury rate in the first year with HPR is significantly higher than in the second (Chi-square = 13.62, $p < .05$), to an extent which could hardly be coincidental.

Is the observed trend a vehicle-age related phenomenon, as has been observed in some other analyses of State data (e.g., [20], pp. 56-66)? It does not seem likely: as Tables 4-19, 4-21 and 4-22 will show, there is no trend whatsoever for fractures, concussions and minor blunt impact trauma; it is unlikely that a vehicle age-related trend

TABLE 4-16

HEAD* INJURIES WITH SEVERE BLEEDING, FRONT SEAT OCCUPANTS IN FRONTAL CRASHES, BY TYPE OF GLAZING (NEW YORK STATE, 1974)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Reduction for HPR (%)
Last w/o HPR	348	9175	37.93	
First with HPR	278	10,925	25.45	33
Last 2 w/o HPR	537	14,400	37.29	
First 2 with HPR	496	22,827	21.73	42
Last 3 w/o HPR	649	17,383	37.34	
First 3 with HPR	767	38,347	20.00	46
Last 4 w/o HPR	693	18,777	36.91	
First 4 with HPR	946	53,539	17.67	52

*Head, face or neck

exists for one type of injury but not at all for others. Moreover, a closer examination of the injury rates in Table 4-16 shows no long-term trend. The injury rate for pre-HPR cars is almost flat at 37 per 1000. For post-HPR cars, the moving average shown in Table 4-16 drops gradually but what really happened is that the injury rate for the first year with HPR was 25 per 1000 and for all years after that it was reasonably close to 18. In other words, there was no trend, but a large drop from 37 to 25 in the first year of HPR (1966) and a second drop from 25 to 18 in 1967.

Could the second drop have been the result of another safety device, viz., more crashworthy steering assemblies or padding on the top of the instrument panel? Not likely: these two devices would almost surely have a greater effect on fractures or blunt impact trauma than on lacerations yet, as Tables 4-19, 4-21 and 4-22 show, nothing happened to those injuries in 1967. Also, if the effect had been due to the steering assembly, it would be found only for drivers; if due to the instrument panel, it would be found mainly for passengers--but Table 4-17 shows more or less the same effect for drivers and passengers. The only difference is that the pre-HPR laceration risk is higher for passengers than for drivers, because passengers do not have a steering wheel between their heads and the windshields. The post-HPR injury risk is about the same at both positions; thus HPR glazing is somewhat more effective for passengers than drivers.

Could the diminished effect in model year 1966 be due to data coding errors, viz., police inadvertently coding 1965 (pre-HPR) cars as MY 1966? A check of VINs showed nearly 100 percent correct coding of the model year in New York State.

TABLE 4-17

HEAD INJURIES WITH SEVERE BLEEDING, BY SEAT POSITION, FRONT SEAT OCCUPANTS IN FRONTAL CRASHES, BY TYPE OF GLAZING (NEW YORK STATE, 1974)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Reduction for HPR (%)
		DRIVERS		
Last w/o HPR	199	6234	31.92	
First with HPR	185	7516	24.61	23
Last 2 w/o HPR	313	9811	31.90	
First 2 with HPR	326	15,808	20.62	35
Last 3 w/o HPR	387	11,878	32.58	
First 3 with HPR	519	26,628	19.49	40
Last 4 w/o HPR	414	12,847	32.22	
First 4 with HPR	645	37,284	17.30	46
		FRONT SEAT PASSENGERS		
Last w/o HPR	149	2941	50.66	
First with HPR	93	3409	27.28	46
Last 2 w/o HPR	224	4589	48.81	
First 2 with HPR	170	7019	24.22	50
Last 3 w/o HPR	262	5505	47.59	
First 3 with HPR	248	11,719	21.16	56
Last 4 w/o HPR	279	5930	47.05	
First 4 with HPR	301	16,255	18.52	61

Could the enhanced effect in 1967 be due to a glazing change documented in the literature, viz., use of thinner glass layers? No: GM did not use thinner glass until 1971 [28], Chrysler in 1976 [23], Ford in 1978 [13]. Also, in 1967-68, only a small number of models changed windshield installation method (see Table 1-1).

Table 4-18 calculates effectiveness separately for the three major domestic manufacturers. General Motors and Chrysler attain an effectiveness of 40 percent immediately in 1966 and escalate a few percent in subsequent years. But Ford starts with a 22 percent injury reduction and escalates rapidly, catching up with GM and Chrysler by the fourth year; thus, Ford is the principal source of the MY 1966 anomaly. But all three manufacturers are remarkably consistent outside of 1966: the pre-HPR laceration rate is nearly 37 per 1000 at each company, each year; the laceration rate in 1967 and 1968 is close to 18 for all 3 producers.

It is concluded that the most valid estimate of HPR effectiveness is obtained by comparing the 1967-68 laceration rate to the pre-HPR rate. The effectiveness is on the order of 50 percent. There is something anomalous in the 1966 injury rates, especially at Ford but also to a lesser extent elsewhere, for which there is no apparent explanation, but which leads to an underestimate of HPR effectiveness.

The 50 percent reduction of "severe bleeding" in New York State data is entirely compatible with NCSS results on AIS $\geq$ 2 lacerations (55-60 percent reduction in Table 4-12). After all, not every injury coded as "severe bleeding" by police is necessarily a laceration (it could be bloody nose) or an AIS $\geq$ 2 injury. Thus, it is appropriate for the New York estimate to be slightly lower than NCSS.

TABLE 4-18

HEAD INJURIES WITH SEVERE BLEEDING, BY MANUFACTURER, FRONT SEAT OCCUPANTS IN FRONTAL CRASHES, BY TYPE OF GLAZING (NEW YORK STATE, 1974)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Reduction for HPR (%)
		GENERAL MOTORS		
Last w/o HPR	195	5223	37.33	
First with HPR	134	5956	22.50	40
Last 2 w/o HPR	303	8346	36.30	
First 2 with HPR	246	12,293	20.01	45
Last 3 w/o HPR	362	10,000	36.20	
First 3 with HPR	379	20,499	18.49	49
Last 4 w/o HPR	382	10,747	35.54	
First 4 with HPR	460	28,729	16.01	55
		FORD		
Last w/o HPR	86	2068	41.59	
First with HPR	87	2670	32.58	22
Last 2 w/o HPR	123	3025	40.66	
First 2 with HPR	144	5697	25.28	38
Last 3 w/o HPR	149	3654	40.78	
First 3 with HPR	200	9314	21.47	47
Last 4 w/o HPR	159	4055	39.21	
First 4 with HPR	239	12,902	18.52	53
		CHRYSLER		
Last w/o HPR	63	1616	38.99	
First with HPR	49	2068	23.69	39
Last 2 w/o HPR	98	2546	38.49	
First 2 with HPR	92	4343	21.18	45
Last 3 w/o HPR	121	3096	39.08	
First 3 with HPR	162	7571	21.39	45
Last 4 w/o HPR	135	3272	41.26	
First 4 with HPR	214	10,441	20.50	50

Table 4-19 confirms the NCSS finding that HPR windshields reduce the likelihood of facial fractures. The sequence of effectiveness estimates--26, 27, 27 and 28 percent--leaves little doubt that the actual reduction is in the 25-30 percent range. The reduction applies to facial fractures due to any contact source. Table 4-3 (the NCSS analysis, which was based on a sample one-tenth as large) suggested that the reduction in fractures due to windshield contacts alone could be anywhere from 20 to 60 percent. The New York data strongly support the upper end of the range: they show HPR windshields eliminate 25-30 percent of facial fractures from any source; only about half of the facial fractures in NCSS pre-HPR cars are due to the windshield; thus, HPR windshields would have to eliminate about 50-60 percent of the facial fractures due to contacting the glass.

4.3.2 Minor lacerations

Table 4-20 shows that HPR windshields have at best, a modest effect on injuries characterized as "minor bleeding" from the face or head. The sequence of effectiveness estimates--3, 6, 11 and 16 percent--creates the same ambiguities as the one for serious lacerations (see Table 4-16; the sequence there was 33, 42, 46, 52) but with the big difference that it starts 30 points lower. If this sequence were indicative of a vehicle age-related trend it would suggest that the true effect of HPR is close to zero. The injury rates in Table 4-20 do show a steady decrease from 1962 through 1969 (except from 1964 to 1965), supporting the concept of an age trend. On the other hand, no such trend appears for any of the other injury types, so the year-to-year reductions in Table 4-20 might be due to factors other than vehicle age. In that case the best estimate of the pre-HPR injury rate (taking into

TABLE 4-19

FACIAL* FRACTURES, FRONT SEAT OCCUPANTS IN FRONTAL CRASHES, BY TYPE OF GLAZING (NEW YORK STATE, 1974)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Reduction for HPR (%)
Last w/o HPR	35	9175	3.81	
First with HPR	31	10,925	2.84	26
Last 2 w/o HPR	60	14,400	4.17	
First 2 with HPR	69	22,827	3.02	27
Last 3 w/o HPR	71	17,383	4.08	
First 3 with HPR	114	38,347	2.97	27
Last 4 w/o HPR	72	18,777	3.83	
First 4 with HPR	148	53,539	2.76	28

*Head, face or neck

TABLE 4-20

HEAD* INJURIES WITH MINOR BLEEDING, FRONT SEAT OCCUPANTS IN FRONTAL CRASHES, BY TYPE OF GLAZING (NEW YORK STATE, 1974)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Reduction for HPR (%)
Last w/o HPR	1037	9175	113.02	
First with HPR	1203	10,925	110.11	3
Last 2 w/o HPR	1596	14,400	110.83	
First 2 with HPR	2374	22,827	104.00	6
Last 3 w/o HPR	1933	17,383	111.20	
First 3 with HPR	3793	38,347	98.91	11
Last 4 w/o HPR	2120	18,777	112.90	
First 4 with HPR	5090	53,539	95.07	16

*Head, face or neck

account adequacy of sample size and proximity to the HPR transition year) is obtained by using 1964-65 model cars. The best estimate for post-HPR would be based on the 1967 models only (the 1966 cars have already been suspected of anomalously high laceration rates). The resultant injury reduction would be 10 percent.

In other words, the reduction of "minor bleeding" from any contact source is at best 10 percent and quite possibly close to zero.

That creates a possible inconsistency with NCSS results (Section 4.1.2), which suggested a 35 percent reduction of AIS 1 lacerations by the windshield (subject to considerable sampling error). The best explanation for the discrepancy would appear to be that NCSS investigators and New York police used different definitions of "minor" injury. Specifically, many AIS 1 lacerations were probably classified as "severe bleeding" in New York, but hardly any AIS 2 lacerations as "minor bleeding." The evidence for that statement is that "severe facial bleeding" is much more common in New York data (37 per 1000 persons according to Table 4-16) than AIS $\geq$ 2 lacerations in NCSS (22 per 1000 persons, according to Table 4-12) despite the fact that NCSS, which is a towaway file, has twice as high an overall injury rate as New York. In other words, HPR windshields are fairly effective in mitigating the relatively more severe "minor" lacerations--those coded AIS 1 in NCSS but "severe bleeding" in New York.

If HPR glazing is indeed effective at mitigating those "AIS 1.5" lacerations, it is probably because the glass cracks into smaller pieces than for pre-HPR windshields and the smaller pieces cause less severe cuts.

But it is also possible that the NCSS result is merely overstated due to sampling error and the New York data give a more valid indication of effectiveness.

4.3.3 Blunt impact trauma

The NCSS analysis (Table 4-5) showed an increase in concussions which was not statistically significant. New York State data, with 10-20 times as large a sample of concussions, set the record straight. Table 4-21 indicates that HPR glazing had essentially no effect on concussions and "internal" head injuries--the sequence of effectiveness estimates is 14, 1, 4 and 5 percent. The result is consistent with laboratory tests which showed little or no change in Head Injury Criterion as a result of HPR (see Section 2.1).

Table 4-22 shows that HPR glazing also had little or no effect on blunt impact trauma (headaches and contusions) or whiplash. The sequence of effectiveness estimates is 4, 4, 0 and 1 percent. In fact, the risk of those types of injuries remained unchanged over the entire span of model years analyzed (1962-69). The ambiguities which occurred in the NCSS results (Table 4-6) are undoubtedly due to sampling error.

4.3.4 Interaction with windshield mounting method

There are two questions concerning possible interactions between the type of glazing and the windshield installation method. First, could any of the preceding estimates of HPR windshield effectiveness have been biased because the post-HPR group contains a larger proportion of adhesively bonded windshields? Chapter 6 is

TABLE 4-21

CONCUSSIONS*, FRONT SEAT OCCUPANTS IN FRONTAL CRASHES, BY TYPE OF GLAZING (NEW YORK STATE, 1974)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Reduction for HPR (%)
Last w/o HPR	92	9175	10.03	
First with HPR	94	10,925	8.60	14
Last 2 w/o HPR	135	14,400	9.38	
First 2 with HPR	211	22,827	9.24	1
Last 3 w/o HPR	167	17,383	9.61	
First 3 with HPR	355	38,347	9.26	4
Last 4 w/o HPR	183	18,777	9.75	
First 4 with HPR	498	53,539	9.30	5

*Concussions plus "internal" injuries of the head, face or neck

TABLE 4-22

MINOR BLUNT-IMPACT HEAD INJURIES*, FRONT SEAT OCCUPANTS IN FRONTAL CRASHES, BY TYPE OF GLAZING (NEW YORK STATE, 1974)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Reduction for HPR (%)
Last w/o HPR	795	9175	86.65	
First with HPR	912	10,925	83.48	4
Last 2 w/o HPR	1241	14,400	86.18	
First 2 with HPR	1895	22,827	83.02	4
Last 3 w/o HPR	1467	17,383	84.39	
First 3 with HPR	3240	38,347	84.49	none
Last 4 w/o HPR	1590	18,777	84.68	
First 4 with HPR	4478	53,539	83.64	1

*Contusions and complaints of pain to the head, face or neck devoted in its entirety to showing that the windshield installation method had little or no effect on injury risk--thus, it would not bias HPR effectiveness estimates.

Second, are HPR windshields equally effective when they are mounted by rubber gaskets or by an adhesive? Table 4-23 shows they are about equally effective in either case.

4.4 Texas data on overall injury rates

Since Texas data do not specify the body region or type of injury, they cannot be used for detailed analyses, but the 1972-74 accident files do confirm that HPR windshields reduced injuries that involved substantial bleeding.

4.4.1 Contingency table analyses

Texas police classify nonfatal injuries in levels A, B or C, as was explained in Section 3.4. Level A is defined to include not only the really serious injuries but also "deep bleeding wounds"--i.e., significant lacerations. Levels B and C mainly include blunt impact trauma, mostly minor. Thus, HPR windshields should primarily mitigate level A injuries.

Table 4-24 confirms that HPR windshields reduce level A injuries in frontal crashes. Drivers in cars of the first model year with HPR had a 12 percent lower level A injury rate than in cars of the last year before HPR. It is a statistically significant reduction (Chi-square = 10.77, $p < .05$). The remainder of the sequence of effectiveness estimates shown in Table 4-24 is not meaningful because energy-absorbing steering columns, introduced in 1967-68, significantly

TABLE 4-23

HEAD INJURIES WITH SEVERE BLEEDING, BY TYPE OF GLAZING AND WINDSHIELD INSTALLATION METHOD, FRONT SEAT OCCUPANTS IN FRONTAL CRASHES (NEW YORK STATE, 1974)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Reduction for HPR (%)
		WINDSHIELDS MOUNTED WITH RUBBER GASKETS		
Last w/o HPR	133	3296	40.35	
First with HPR	89	3259	27.31	32
Last 2 w/o HPR	278	7593	36.61	
First 2 with HPR	157	6803	23.08	37
		ADHESIVELY BONDED WINDSHIELDS		
Last w/o HPR	211	5732	36.81	
First with HPR	178	7479	23.80	35
Last 2 w/o HPR	249	6512	38.23	
First 2 with HPR	324	15,639	20.72	46

TABLE 4-24

LEVEL A INJURY RATES, DRIVERS IN FRONTAL CRASHES, BY TYPE OF GLAZING (TEXAS, 1972-74)

Model Years	n of Injuries	N of Drivers	Injuries per 1000 Drivers	Reduction for HPR (%)
Last w/o HPR	1362	44,361	30.70	
First with HPR	1282	47,351	27.07	12*
Last 2 w/o HPR	2404	76,774	31.31	
First 2 with HPR	2394	96,583	24.79	21
Last 3 w/o HPR	3428	108,274	31.66	
First 3 with HPR	3560	154,193	23.09	27
Last 4 w/o HPR	3884	121,793	31.89	
First 4 with HPR	4627	212,840	21.74	32

*Statistically significant reduction: Chi-square = 10.77, $p < .05$

reduced serious torso injuries. Thus, the higher effectiveness estimates in the ±2, ±3, and ±4 year comparisons are not attributable to HPR alone.

Table 4-25 shows that HPR windshields had little or no effect on level B and C injuries (primarily blunt impact trauma) in frontal crashes. Drivers in cars of the first year with HPR had a 1 percent higher risk of B or C injury than in cars of the last year before HPR. It is not a significant increase (Chi-square = 0.45, $p > .05$).

4.4.2 Regression analyses

An inspection of Tables 4-24 and 4-25 reveals that Texas injury rates are influenced by vehicle age and energy-absorbing steering columns as well as by the HPR windshield. Since multiple calendar years of Texas data are available, it is appropriate to use regression analysis to sort out the various effects (see Section 3.9.1).

When the dependent variable is the level A injury rate, the equation that best fits the observed, weighted data is

$$\begin{aligned} \text{Rate (\%)} = {} & 1.421 - 0.252\ \text{HPR} \\ & + 0.228\ \text{AGE} - 0.0074\ \text{AGE}^2 \\ & - 0.418\ \text{STD203} \\ & + 0.565\ \text{CY72} + 0.296\ \text{CY73} \end{aligned}$$

and $R^2 = .96$ and df = 17 (a very good fit).

TABLE 4-25

LEVEL B OR C INJURIES, DRIVERS IN FRONTAL CRASHES, BY TYPE OF GLAZING (TEXAS, 1972-74)

Model Years	n of Injuries	N of Drivers	Injuries per 1000 Drivers	Reduction for HPR (%)
Last w/o HPR	4681	44,361	105.52	
First with HPR	5061	47,351	106.88	-1*
Last 2 w/o HPR	8212	76,774	106.96	
First 2 with HPR	9880	96,583	102.30	4
Last 3 w/o HPR	11,809	108,274	109.07	
First 3 with HPR	15,355	154,193	99.58	9
Last 4 w/o HPR	13,356	121,793	109.66	
First 4 with HPR	20,623	212,840	96.89	12

*Not a significant change: Chi-Square = 0.45, p > .05

When the current average values 7, 1, .32 and .35 are substituted for AGE, STD203, CY72 and CY73, respectively, the predicted injury rates are

- o 2.52 percent without HPR windshields
- o 2.27 percent with HPR windshields

In other words, HPR reduces A level injuries by 10 percent--approximately the same as was found in the ± 1 year comparison of Table 4-24, the Texas contingency table analysis. Since the F-value for the HPR term in the regression is 4.55 (df = 1,17; $p < .05$), the injury reduction for HPR is statistically significant.

Incidentally, the regression coefficient for STD203 corresponds to a 16 percent reduction of level A injuries in frontal crashes for the energy-absorbing steering column. This is almost the same as the 17.5 percent reduction of hospitalizations found in NHTSA's evaluation of the columns, which was based on NCSS data [18], p. 17. It provides some assurance that the regression model is functioning correctly.

When the dependent variable is the rate of injuries of levels B or C, the regression equation is

$$\begin{aligned} \text{Rate (\%)} &= 8.274 + 0.473\ \text{HPR} \\ &+ 0.259\ \text{AGE} + 0.007\ \text{AGE}^2 \\ &- 0.634\ \text{STD203} \\ &- 0.311\ \text{CY72} \quad -0.240\ \text{CY 74} \end{aligned}$$

and $R^2 = .96$ and df = 17.

The predicted injury rates are

- o 9.46 percent without HPR windshields
- o 9.93 percent with HPR windshields

In other words, level B and C injuries increased by 5 percent--somewhat more than the increase found in Table 4-25. Since the F-value for the HPR term is 6.35 (df = 1,17; $p < .05$), the increase is statistically significant. Nevertheless, it should not be viewed with alarm. Perhaps half of the increase is attributable to the reduction of level A injuries: since police report only one injury per person, a B or C injury would not have been reported in a pre-HPR car if the person had also received level A injuries from the windshield. More importantly, the New York State data did not show increases in any category of head injury. As a result, it is doubtful that this small increase in Texas is really due to HPR.

4.5 Analyses of FARS data

The Fatal Accident Reporting System for 1975-82 is the only file containing enough fatal accidents to allow a possibility of detecting the effects, if any, that windshields may have had on fatality risk. Since FARS does not contain counts of persons involved in non-fatal accidents, the measure of risk is the ratio of fatalities in frontal accidents (the type most likely to be influenced by windshields) relative to a control group of nonfrontal crashes, as was explained in Section 3.5.

4.5.1 Contengency table analyses

Table 4-26 shows little or no effect of HPR windshields on fatality risk in frontal crashes. Front-seat occupants of cars of the first model year with HPR had a 2 percent lower fatality risk (relative to nonfrontal crashes) than in cars of the last model year before HPR. It is not a statistically significant reduction (Chi-square = 0.21, P > .05). There is not much point in adding cars of the second model year with HPR (1967) to the analysis. Most of those cars also had energy-absorbing steering columns, which significantly reduce frontal fatalities, completely obscuring the effect, if any, of HPR (see Table 4-24 for an example of this phenomenon in Texas). Thus the continuation of Table 4-26 is limited to one additional pre-HPR model year, which hardly changes the results.

Another approach possible with FARS is to study only front-seat passengers, who unlike drivers are hardly affected by the steering column. (This approach could not be used with Texas data--see Section 3.4). Table 4-27 shows that FARS yields ambiguous results for passengers. The sequence of effectiveness estimates--6, 12, 11 and 14 percent--suggests a possible but not obvious vehicle age effect. A regression analysis is needed to sort out the various effects.

4.5.2 Regression analysis

Since multiple calendar years of FARS are available, it is appropriate to use regression analysis to sort out the effects of HPR glazing, energy-absorbing steering columns and vehicle age. This makes it possible to study drivers as well as passengers over the full 1962-69 range of model years.

TABLE 4-26

FARS 1975-82: FRONT-SEAT OCCUPANT FATALITIES*
BY TYPE OF GLAZING AND PRINCIPAL IMPACT POINT

Model Years	Fatalities			
	Nonfrontal Impacts	Frontal Impacts	Frontal Reduction for HPR (%)	Chi-Square
Last w/o HPR	2497	2855		
First with HPR	3175	3570	2**	0.21
Last 2 w/o HPR	4092	4753		
First with HPR	3175	3570	3**	1.01

*In domestic passenger cars without energy-absorbing steering columns

**Not a statistically significant change

TABLE 4-27

FARS 1975-82: FRONT-SEAT PASSENGER FATILITIES BY TYPE OF GLAZING AND PRINCIPAL IMPACT POINT

Model Years	Fatalities		
	Nonfrontal Impacts	Frontal Impacts	Frontal Reduction for HPR (%)
Last w/o HPR	1020	971	
First with HPR	1320	1185	6
Last 2 w/o HPR	1682	1632	
First with HPR	2823	1423	12
Last 3 w/o HPR	2136	2087	
First 3 with HPR	4730	4091	11
Last 4 w/o HPR	2366	2331	
First 4 with HPR	6982	5889	14

When the dependent variable is the logarithm of the ratio of frontal to nonfrontal fatalities (see Section 3.9.1), the equation that best fits the observed, weighted data is

$$\begin{aligned} \text{Logodds} = &-0.28 \quad -0.02 \text{ HPR} \\ &+0.07 \text{ AGE} \quad -0.0026 \text{ AGE}^2 \\ &-0.10 \text{ STD203} \\ &+0.005 \text{ CY75} \quad -0.006 \text{ CY76} \quad -0.057 \text{ CY77} \\ &-0.052 \text{ CY78} \quad -0.047 \text{ CY79} \quad -0.005 \text{ CY80} \\ &-0.037 \text{ CY81} \end{aligned}$$

and R^2 = .57 and df = 52.

In other words, the model attributes a 2 percent reduction in frontal fatalities to HPR--exactly the same as was found in the $\pm$ 1 year comparison of Table 4-26.

Since the F-value for HPR in the regression is 0.26 (df = 1,52; $p > .05$) the fatality reduction for HPR is nowhere near statistical significance. Incidentally, the regression attributed a statistically significant 10 percent fatality reduction to energy-absorbing steering columns (STD203). Since the data include front-seat passengers as well as drivers, since front-seat passengers are largely unaffected by the columns and since 73 percent of post-Standard 203 front-seat occupant fatalities are drivers, the observed 10 percent fatality reduction for all front-seat occupants is equivalent to a 13 percent reduction for drivers. (Let D be the proportion of pre-Standard 203 fatalities who were drivers and E be the fatality reduction for drivers. Then solve $D(1-E) + (1-D) = .9$

and D (1 -E) = .73 x .9 for D and E.) This is almost the same as the 12 percent fatality reduction found in NHTSA's evaluation of the columns, which was based on a quite different analysis approach [18], p. 16. It provides some assurance that the regression model functioned correctly.

4.6 Summary: "best" estimates of effectiveness and their confidence bounds

The NCSS and New York analyses strongly confirmed the laboratory findings that HPR windshields greatly reduced the types of injuries associated with penetration of the windshield while having little effect on other injury types. Both files should be considered in preparing "best" estimates of the reductions of the various types of injuries.

o Nonminor (AIS $\geq$ 2) lacerations due to contacting the wind-shield: the NCSS (Table 4-1) and New York (4-16) results strongly support a high effectiveness estimate. In particular, the $\pm$ 5 year comparison for NCSS indicated a 74 percent reduction due to HPR. Since there was no evidence of a vehicle age effect in Table 4-1 and this estimate was based on the largest sample, it is the "best" estimate of effectiveness.

A standard deviation for the effectiveness E, which is a ratio of proportions, is given approximately by

$$S = (1 - E)\ (q_1/(p_1\ n_1) + q_2/(p_2\ n_2))^{1/2}$$

where p_1, q_1, n_1 and p_2, q_2, n_2, with their usual meanings, apply to the pre- and post-standard samples, respectively. For a first approximation of confidence intervals use $E \pm 1.645\ s$, fully recognizing that they overstate the lower bound, especially when s is large.

Based on the data in Table 4-1 (and noting that the table only counts the injuries in the 100 percent sampling stratum), the confidence bonds for effectiveness are 65 to 83 percent. These bonds can be accepted as they are: although the calculation formula may cut them too close, statistically speaking, this is compensated by the fact that the New York results, based on a larger sample, strongly confirm NCSS (see Section 4.3.1).

o Nonminor injuries of the eyes, nose and mouth: the ± 5 year comparison based on NCSS data (Table 4-2) indicates a reduction of 72 percent. Since there is no evidence of an age effect, it is the best estimate. The confidence bounds are 58 to 86 percent.

o Nonminor facial fractures due to windshield contact: The NCSS results (Table 4-3) produced estimates from 25 percent in the ± 1 year comparison to 56 percent at ± 5 years, with a fluctuation that could be ascribed to either vehicle age or sampling error. But the New York data (Table 4-19) with a much larger sample, showed no age effect and strongly supported the ± 5 year comparison on NCSS. Thus, 56 percent is the best estimate of injury reduction. The confidence bounds based on NCSS data and the above formula are 27 to 85 percent. They can be accepted as they are because New York data confirm the NCSS results so strongly.

o Minor lacerations due to windshield contact: the ± 5 year comparison based on NCSS data (Table 4-4) showed a 38 percent reduction. But the New York data (Table 4-20) suggested a much smaller reduction, on the order of 5 to 20 percent (although Section 4.3.2 provided an explanation for why New York results might be lower than NCSS). Laboratory test results and biomechanical analyses also do not support too large a reduction. The confidence bounds for the NCSS results are 20 to 56 percent (when the sample sizes in Table 4-4 are divided by 4 to account for the fact that most of those injury cases are in the 25 percent sampling stratum).

The "best" effectiveness estimate is obtained by averaging the New York and NCSS results: a 25 percent injury reduction. The width of the NCSS confidence bounds offer a guideline for heuristic bounds for this synthetic estimate: 5 to 45 percent.

o Concussions due to contacting the windshield: the New York data (Table 4-21) showed little or no change in the incidence of concussions and "internal" head injuries as a consequence of HPR, confirming laboratory test results showing little change in head impact forces (see Section 2.1). The NCSS data, which showed a nonsignificant increase based on a much smaller sample (Table 4-5) do not deserve as much weight as the New York data. The best estimate is "no change."

o Minor blunt impact trauma: the New York data (Table 4-22) associated little or no change with HPR. They are confirmed by the ± 5 year comparison in NCSS (Table 4-6). The best estimate is "no effect."

o Fatalities due to windshield contact injuries: the FARS analyses (Section 4.4) did not find a statistically significant fatality reduction for HPR, but they did attribute a 2 percent reduction in frontal fatalities to HPR. That would amount to about 200 lives per year. This is not a trivial number: further analysis is required to check if the effect might be real or is merely sampling error.

The New York analyses, however, showed no effect on concussions, confirming laboratory findings that neither HPR nor earlier windshields allow a buildup of impact forces likely to cause dangerous closed-head injury in a normal person. Thus, any fatality reduction for HPR is unlikely to be due to mitigation of closed head injury but rather due to an avoidance of "freak" injuries in which an important artery is lacerated and the victim bleeds to death before receiving needed medical assistance. Could that type of injury avoidance amount to 200 lives saved per year? It would not appear likely, based on a case-by-case analysis of the 11 persons on NCSS with well documented fatal lesions that were attributed to windshield contact. None of the 11 had a lacerative type injury and all had closed head injury or a broken neck. Their other characteristics were

- 4 were also killed by the steering assembly--(not savable by windshield improvements).
- 4 were in crashes with catastrophic damage or were subsequently ejected through the door (difficult to identify contact points correctly; see Section 1.3).

- 2 were over 70 years old (unusually vulnerable to impact).
- 1 had closed head injury without any of the preceding unusual circumstances.

In view of these various findings, the best estimate for fatality reduction is "no change."

CHAPTER 5

THE EFFECT OF WINDSHIELD INSTALLATION METHOD ON WINDSHIELD SEPARATION AND OCCUPANT EJECTION

Analyses of NCSS data on American cars show that adhesively bonded windshields experience about 35-50 percent less bond separation in crashes than do windshields attached to the frame by rubber gaskets. Studies of NCSS, MDAI and FARS data show that the improvement in windshield retention has brought about a commensurate reduction of occupant ejection through the windshield portal.

Prior to Standard 212, windshields in Volkswagens were attached much more loosely than in American cars. Although Volkswagen continued to use rubber gasket installations during the 1970's, the clips that they installed between the gasket and the frame, in response to Standard 212, reduced bond separation and ejection through the windshield portal by 50 percent each. In this chapter, it will be seen that some analyses refer to "German cars" and others to "Volkswagens." The reason is as follows: when large data files were used (FARS, New York, Texas), the analysis of German cars was limited to Volkswagen, where it is relatively clear that clips were installed very close to the beginning of the 1970 model year. For the smaller data files (NCSS, MDAI), the other German makes are included to increase the available sample size, even though it is not as well known when and if similar modifications were made. Thus, throughout the report, results on "German cars" are the ones based on NCSS and/or MDAI; those on

"Volkswagen" are based on the other files. Practically speaking, though, the distinction is of minor importance since Volkswagen accounted for over 85 percent of the German cars sold here during 1965-74.

The procedures and definitions for this chapter's analyses of NCSS, MDAI and FARS data were set forth in Chapter 3.

5.1 NCSS data on windshield bond separation

In every crash, NCSS investigators were required to measure the percentage, if any, of the windshield periphery which had become separated from the frame. The average amount of windshield separation in a sample of cars involved in frontal crashes can be used as a measure of performance of the bonding substance. For example, if there were 10 cars; the bond remained intact in 8 of them; the windshield popped out completely in one; and 20 percent of the bond was separated on one; these 10 cars had an average of 12 percent bond separation. Standard 212 allows a maximum of 25 percent bond separation in a 30 mph barrier test (50 percent in any car equipped with passive restraints).

5.1.1 Overall effect of adhesive bonding on windshield separation

Table 5-1 shows that adhesive bonding reduced the amount of bond separation in domestic cars in frontal crashes by 30-35 percent relative to cars of the same makes and models (as defined in Section 3.1) whose windshields were attached with rubber gaskets. For example, cars of the last model year with rubber gaskets experienced an average of 4.12 percent bond separation. Cars of the first year with adhesive bonding had an average of 2.73 percent bond separation. This is a 34 percent reduction in the average amount of separation. When the NCSS sample is expanded to include the second year before and after the transition to adhesive bonding, the

TABLE 5-1

AMOUNT OF WINDSHIELD BOND SEPARATION, ADHESIVE BONDING VS. RUBBER GASKETS, DOMESTIC CARS IN FRONTAL IMPACTS (NCSS)

Model Years	Unweighted N of Cars	Weighted Average Percentage of Bond Separation	Reduction for Adhesive Bonding (%) Relative	Reduction for Adhesive Bonding (%) Absolute
Last MY w. rubber gaskets	138	4.12		
First MY w. adhesive bonding	180	2.73	34	1.39
Last 2 w. rubber gaskets	278	4.08		
First 2 w. adhesive bonding	397	2.64	35	1.44
Last 3 w. rubber gaskets	388	3.63		
First 3 w. adhesive bonding	622	2.42	33	1.21
Last 4 w. rubber gaskets	455	3.65		
First 4 w. adhesive bonding	828	2.49	32	1.16
Last 5 w. rubber gaskets	515	3.71		
First 5 w. adhesive bonding	1095	2.54	32	1.17

reduction is nearly identical: 35 percent. The reductions for ±3, ±4 and ±5 model years are again nearly the same: 33, 33 and 32 percent, respectively. Thus, NCSS data strongly suggest that the overall reduction is on the order of 30-35 percent.

Those were the relative reductions in bond separation. Another measure of effectiveness is the absolute difference between the averages for rubber and adhesive. Table 5-1 shows that the absolute differences are on the order of 1.2 - 1.4 percent. In other words, the improvement for adhesive bonding is fairly small in absolute terms because the rubber gaskets used in domestic cars were already retaining the windshield well in most crashes.

Whereas the type of bonding substance (rubber vs. adhesive) clearly has an influence on windshield retention, it is certainly not the only factor. Table 5-2 shows larger variations among manufacturers for the same bonding substance than between bonding substances. For example, General Motors had relatively loose rubber gaskets (average separation: 5.04%) but also, in the early years, a fairly loose type of adhesive bond (4.07); thus the reduction for adhesive bonding was only 0.97 percent in absolute terms. Ford had even looser gaskets (5.25) but much tighter adhesive bonding (1.65), for a more substantial 3.60 percent reduction. But Chrysler's rubber gaskets were tighter (2.06) than GM's adhesive bonding; thus, Chrysler only obtained an additional 0.83 reduction when they shifted to adhesive bonding.

All of the differences among domestic manufacturers seem trivial relative to the differences between German and American cars. Prior to Standard 212, the rubber gaskets used on German cars allowed an average of 28.10 percent bond separation in frontal towaway crashes, which was 5 times as much as the loosest domestic brand. German cars essentially provided a

TABLE 5-2

AMOUNT OF WINDSHIELD BOND SEPARATION, ADHESIVE BONDING VS. RUBBER GASKETS, BY MANUFACTURER, FRONTAL IMPACTS (NCSS)

Model Years	Unweighted N of Cars	Weighted Average Percentage of Bond Separation	Reduction for Adhesive Bonding (%) Relative	Reduction for Adhesive Bonding (%) Absolute
		GENERAL MOTORS		
Last 5 MY w. rubber gaskets	115	5.04		
First 5 MY w. adhesive bonding	642	4.07	19	0.97
		FORD		
Last 5 MY w. rubber gaskets	321	5.25		
First 5 MY w. adhesive bonding	349	1.65	69	3.60
		CHRYSLER		
Last 5 MY w. rubber gaskets	252	2.06		
First 5 MY w. adhesive bonding	233	1.23	40	0.83
		GERMANY		
Rubber gaskets (1965-69)	57	28.10		
		JAPAN		
Rubber gaskets (1965-74)	73	2.00		
Adhesive bonding (1971-74)	18	0.66	67	1.34

true "pop-out" windshield, in accordance with the recommendations of German engineers such as Rodloff and Breitenbuerger who believed it to be desirable from a safety standpoint (see Sections 1.5 and 2.2). American windshields, even with rubber gaskets and before Standard 212, were nothing of the sort. This could be part of the explanation for the discrepancies between German and American laboratory tests on windshield installation methods (Section 2.2): American rubber gaskets are much closer to adhesive bonding than to German gaskets, in regard to bond separation. It may be a reason why American engineers found the bonding method to be of less importance than the Germans did.

Table 5-2 shows that Japanese windshield installations were as tight as American ones, both in the cars with rubber gaskets (2.00) and adhesive bonding (0.66).

5.1.2 Overall effect of Standard 212 on windshield separation

What influence did Standard 212 (effective date 1-1-70) have on windshield retention in frontal crashes? Did it cause the changeover from rubber gaskets to adhesive bonding? Did it result in other changes in windshield installation methods?

Table 5-3 suggests that Standard 212 had little or no effect on American and Japanese cars but was associated with a tremendous improvement in windshield retention in German cars.

Prior to Standard 212, German cars had an average of 28.10 percent bond separation in all frontal towaway crashes. Evidently, action had to be taken to meet Standard 212, which allows at most 25 percent separation in a 30 mph barrier collision (far more severe than the average towaway). German manufacturers did not choose to change over to adhesive bonding; instead, Volkswagen installed clips that hold the gasket more securely to the

TABLE 5-3

AMOUNT OF WINDSHIELD BOND SEPARATION, BEFORE VS. AFTER STANDARD 212*, BY COUNTRY OF MANUFACTURE AND INSTALLATION METHOD, FRONTAL IMPACTS (NCSS)

Model Years	Unweighted N of Cars	Weighted Average Percentage of Bond Separation	Reduction for Standard 212 (%)	
			Relative	Absolute
UNITED STATES - RUBBER GASKETS				
Last 5 before Std. 212	291	3.98		
First 5 after Std. 212	372	5.06	-27	-1.08
UNITED STATES - ADHESIVE BONDING				
Last 5 before Std. 212	992	3.44		
First 5 after Std. 212	1909	2.29	33	1.15
GERMANY - RUBBER GASKETS				
Last 5 before Std. 212	57	28.10		
First 5 after Std. 212	156	13.87	51	14.23
JAPAN - RUBBER GASKETS				
Last 5 before Std. 212	9	3.96		
First 5 after Std. 212	66	1.68	58	2.28

*Effective date: 1-1-70

pinch-weld frame. Average bond separation was 13.87 percent in German cars of the first 5 model years after Standard 212; this absolute improvement of 14.23 percent over pre-standard is incomparably larger than the effect of any other change in other cars, e.g., the effect of changing from rubber gaskets to adhesive bonding in American cars.

The performance of German post-standard cars puts everything in perspective. They comply with Standard 212; nevertheless, their 13.87 percent average bond separation is considerably greater than any group of American or Japanese cars--even the loosest pre-standard rubber gaskets. It can be concluded that Standard 212 is not directly responsible for the shift from gaskets to bonding in American cars or for any other major change--for the simple reason that American cars already could have met the standard easily before 1970 and with the types of rubber gaskets used in this country. In fact, Ford discontinued its Falcon, which had a tight adhesive bond, in 1970--the very year that Standard 212 took effect--and replaced it with the Maverick, which probably had one of the loosest rubber gaskets ever installed in American cars of the 1960-80 era, yet easily met Standard 212. For that reason, domestic cars with rubber gaskets of the first 5 model years after Standard 212 actually had 1.08 percent more bond separation than those of the last 5 pre-standard years (see Table 5-3). Domestic cars with adhesive bonding had 1.15 percent less bond separation after Standard 212, primarily because GM's early (1965-69) adhesive bonding was looser than the later practice of the domestic manufacturers. But the subsequent tightening could hardly have been forced by the standard.

5.1.3 Overall effect of polyurethane sealant on windshield separation

General Motors began to bond windshields to the frame with a polyurethane sealant in model year 1973, superseding the use of butyl adhesive tape; AMC made a similar shift in 1974. McKale of GM suggested to the author that this modification of adhesive bonding techniques may have been as influential as the earlier change from rubber gaskets to adhesive bonding [29]. Clark of NHTSA likewise remarked that polyurethane bonding was found to be much stronger than butyl tape in laboratory tests. Table 5-4 suggests, however, that the choice of adhesive had at most a limited effect on windshield separation in frontal crashes. Cars of the first model year with polyurethane sealant had only 0.21 percent less bond separation (in absolute terms) than those of the last model years with butyl tape. As more model years are included in the comparison, the reduction becomes slightly larger, but never exceeds 1 percent. The observed reductions are likely due to factors other than the choice of sealant--e.g., the older cars being in more severe crashes or the exceptional looseness of some of GM's early adhesive installations. As was shown in Table 5-2, Ford, which used mostly butyl tape throughout the years covered by NCSS, had even tighter bonding than GM's polyurethane installations.

Since Table 5-4 as well as the analyses of windshield separation by Delta V (sections 5.1.4 and 5.1.5) show little difference between butyl tape and polyurethane, the two types of adhesive bonding will not be analyzed separately in the studies on occupant ejection (Sections 5.2, 5.3 and 5.4) or injury risk within the vehicle (Chapter 6).

TABLE 5-4

AMOUNT OF WINDSHIELD BOND SEPARATION, POLYURETHANE SEALANT VS. BUTYL TAPE, GM AND AMC CARS IN FRONTAL IMPACTS (NCSS)

Model Years	Unweighted N of Cars	Weighted Average Percentage of Bond Separation	Reduction for Polyurethane Sealant (%) Relative	Absolute
Last MY w. butyl tape	264	3.24		
First MY w. polyurethane	312	3.03	6	0.21
Last 2 w. butyl tape	498	2.68		
First 2 w. polyurethane	527	2.52	6	0.16
Last 3 w. butyl tape	748	2.56		
First 3 w. polyurethane	714	2.93	21	0.53
Last 4 w. butyl tape	984	2.99		
First 4 w. polyurethane	952	2.06	31	0.93
Last 5 w. butyl tape	1174	3.15		
First 5 w. polyurethane	1234	2.18	31	0.97

5.1.4 Amount of windshield separation as a function of Delta V

Standard 212 does not allow more than 25 percent bond separation in a staged frontal barrier collision at 30 mph. How does the requirement compare to the actual performance of windshields in frontal highway crashes at 30 mph, or at other speeds? The next two sections measure the performance of windshield installations as a function of crash velocity (Delta V). Here, the performance criterion is the average (or expected) amount of bond separation. In Section 5.1.5, the performance criterion is the probability of severe (over 50%) bond separation.

Linear regression was used to estimate the expected amount of bond separation as a function of Delta V and windshield installation method. The installation method was expressed by 4 variables:

BUTYL = 1 if installed with butyl tape, 0 otherwise

URETHANE = 1 if sealed w. polyurethane, 0 otherwise

STD 212 = 1 for MY 70-79, 0 for MY 60-69

GERMAN = 1 for German cars, 0 for American cars

Preliminary stepwise regressions tested some additional variables. They showed bond separation is far more correlated with Delta V squared that with Delta V, understandably so because the force on the bond is proportional to the square of the velocity change. Vehicle age should be added to the independent variable list but not age squared. The presence/absence of HPR glazing did not correlate significantly with bond separation, nor did the presence/absence of occupant contact with the windshield (as indicated by the NCSS variable V1GLDWND). Thus, the independent variables for the final regression model were Delta V squared, the four windshield installation method variables, vehicle age plus appropriate interaction terms. Multiple R squared was 0.31 with df = 3535, a good fit considering that the model is predicting the dependent variable for each individual car, not the average for a group of cars in a given speed range. The regression coefficients and their t-values were:

Variable	Reg. Coefficient	t-Value
INTERCEPT	-2.77	
DVSQ	.0267	19.17 ($p < .05$)
BUTYL	.948	1.04
BUTYL x DVSQ	-.00797	-4.84 ($p < .05$)
URETHANE	.277	0.32
URETHANE x DVSQ	-.00941	-5.14 ($p < .05$)
STD212	.84	0.71
BUTYL x STD212	-1.70	-1.52
GERMAN	12.43	4.78 ($p < .05$)
GERMAN x DVSQ	.0277	5.33 ($p < .05$)
GERMAN x STD212	-9.24	-3.14 ($p < .05$)
GERMAN x STD212 x DVSQ	-.0158	-2.78 ($p < .05$)
AGE	.08	0.83

In other words, adhesive bonding significantly reduced windshield separation in American cars--butyl tape and polyurethane sealant being about equally effective. Standard 212 did not significantly affect American cars. German cars once had incomparably looser windshields than American cars but they improved dramatically as a result of the clips installed in response to Standard 212. Figure 5-1 graphs the average amount of bond separation as a function of Delta V by windshield installation method and Standard 212 compliance, for American and German cars.

FIGURE 5-1: WINDSHIELD BOND SEPARATION AS A FUNCTION OF DELTA V, BY WINDSHIELD INSTALLATION METHOD AND STANDARD 212 COMPLIANCE, DOMESTIC AND GERMAN CARS IN FRONTAL IMPACTS (NCSS REGRESSION RESULTS)

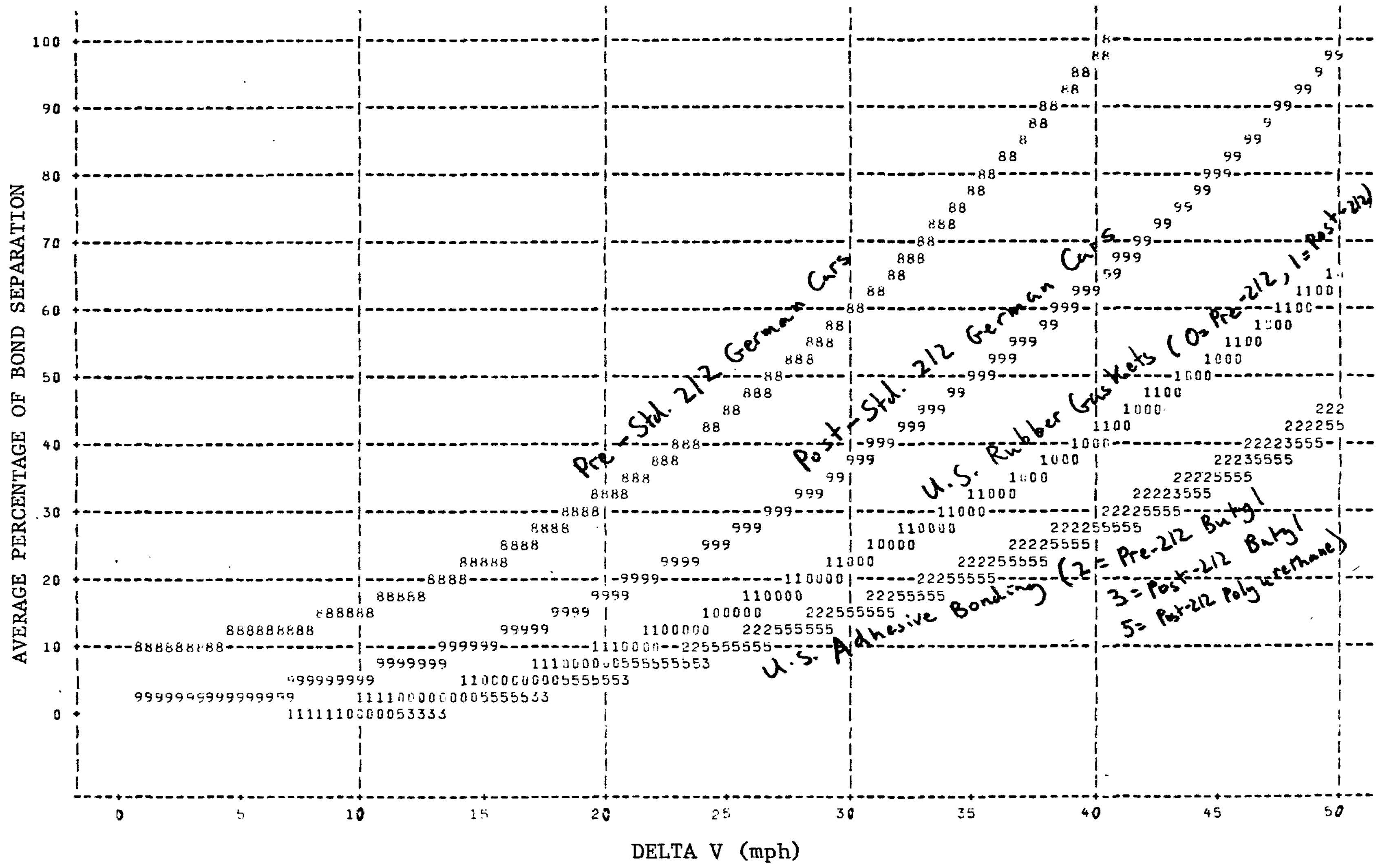


Table 5-5 shows the amount of bond separation predicted by the regression in 30 mph frontal highway crashes (i.e., at the speed used for the Standard 212 compliance test); it shows the crash speed at which 25 percent bond separation (the maximum allowed in the compliance test) can be expected; also the speed at which 50 percent separation can be expected. Butyl tape and polyurethane sealant were about equally effective, resulting in an average of 14-16 percent bond separation at 30 mph. They were significantly better than rubber gaskets on American cars, which allowed 22-23 percent separation at 30 mph. Nevertheless, even pre-standard American rubber gaskets were well within the limits of Standard 212--as evidenced by the post-Standard 212 German cars, which allowed 37 percent separation. In fact, the gap between domestic gaskets and adhesive bonding was smaller than the gap between pre-standard domestic gaskets and post-standard German gaskets. The loosest installation by far, however, was the pre-Standard 212 German rubber gasket, which allowed 59 percent bond separation at 30 mph. The benefit of clipping German gaskets to the pinch-weld frame (22 percent reduction of windshield separation at 30 mph) was much greater than the benefit of converting from rubber gaskets to adhesive bonding in American cars.

The speeds at which 25 percent windshield separation can be expected in highway crashes can be compared to the 30 mph compliance test speed for Standard 212 (at which separation must not exceed 25 percent). These speeds are always above 30 mph for American cars. It was only 16 mph for pre-standard German cars. It is still only 25 mph for the post-standard German cars on NCSS, suggesting that the typical 30 mph highway accident is a tougher test of windshield retention than the barrier compliance test.

TABLE 5-5

WINDSHIELD BOND SEPARATION AS A FUNCTION OF DELTA V, BY WINDSHIELD INSTALLATION METHOD AND STANDARD 212 COMPLIANCE, DOMESTIC AND GERMAN CARS IN FRONTAL IMPACTS (NCSS REGRESSION RESULTS)

Country	Windshield Installation Method	Pre/Post Standard 212	Expected Percent of Separation at 30 mph	Speed at Which 25% Sep. Expected	Speed at Which 50% Sep. Expected
United States	rubber gasket	pre	22	32	44
		post	23	31	44
	butyl type	pre	16	37	52
		post	15	38	53
	polyurethane	post	14	39	54
Germany	rubber gasket	pre	59	16	27
		post	37	25	35

5.1.5 Probability of severe windshield separation as a function of Delta V

When windshield separation is severe--say, 50 percent or more--an occupant with a frontal trajectory has a significant risk of ejection through the windshield portal. But small amounts of windshield separation, such as 5, 10 or 15 percent are not likely to allow ejection. Thus, perhaps, the "proportion of windshields with greater than 50 percent bond separation" is a measure of performance more directly related to ejection risk than the "average amount of separation," since the latter can be influenced by changes at the low end of the separation scale, which are not as relevant to ejection risk. Unfortunately, the former is not as amenable to statistical analysis.

Table 5-6 shows the proportion of frontally-impacted cars in which 50 percent or more of the windshield bond separated, by Delta V group and windshield installation method. It is clear from the table that this proportion is low in domestic cars with rubber gaskets when Delta V is below 25 mph; in domestic cars with adhesive bonding when Delta V is below 30 mph. But in German cars prior to Standard 212, the problem already began at 15 mph.

The cell entries in Table 5-6 were entered in logistic regressions as the dependent variable; the independent variables were Delta V and the variables BUTYL, URETHANE, STD 212 and GERMAN which were defined in the preceding section. Data points were weighted by the sample sizes shown in the lower part of Table 5-6. (see also Section 3.9.2 for discussion of logistic regression.) Preliminary regressions showed that the dependent variable was far more correlated with Delta V than with Delta V squared.

TABLE 5-6

SEPARATION OF MORE THAN HALF OF THE WINDSHIELD BOND, BY WINDSHIELD INSTALLATION METHOD AND STANDARD 212 COMPLIANCE, DOMESTIC AND GERMAN CARS IN FRONTAL IMPACTS (NCSS)

Percent of Cars in which more than Half of the Bond Separated

	Domestic Cars					German Cars	
	Rubber Gaskets		Butyl Tape		Polyurethane	Rubber Gaskets	
Delta V	Pre-Std 212	Post-Std 212	Pre-Std 212	Post-Std 212	Post-Std 212	Pre-Std 212	Post-Std 212
1-4	1	0	0	0	0	--	0
5-9	0	1	0	0	0	0	1
10-14	0	0	2	0	1	8	6
15-19	4	1	3	1	2	71	28
20-24	14	6	3	1	4	44	25
25-29	34	22	9	4	5	67	9
30-34	36	28	25	23	12	100	33
35-39	12	54	44	13	22	100	50
40+	67	50	82	44	51	100	92
All Speeds	3.8	3.4	2.7	1.3	2.0	25.4	11.5

Unweighted Sample Sizes for Preceding Table

1-4	9	10	9	32	31	0	5
5-9	66	81	127	266	191	6	28
10-14	98	75	185	326	253	11	26
15-19	60	49	140	233	169	5	16
20-24	43	35	88	125	111	6	13
25-29	23	22	45	81	67	6	8
30-34	11	16	25	49	48	5	6
35-39	7	10	13	18	18	3	6
40+	12	12	22	40	34	1	12
All Speeds	329	310	654	1170	922	43	120

They showed little interaction between Delta V and the other variables. The final regression model, which had R squared equal to 0.85 with df = 54 (a good fit), had

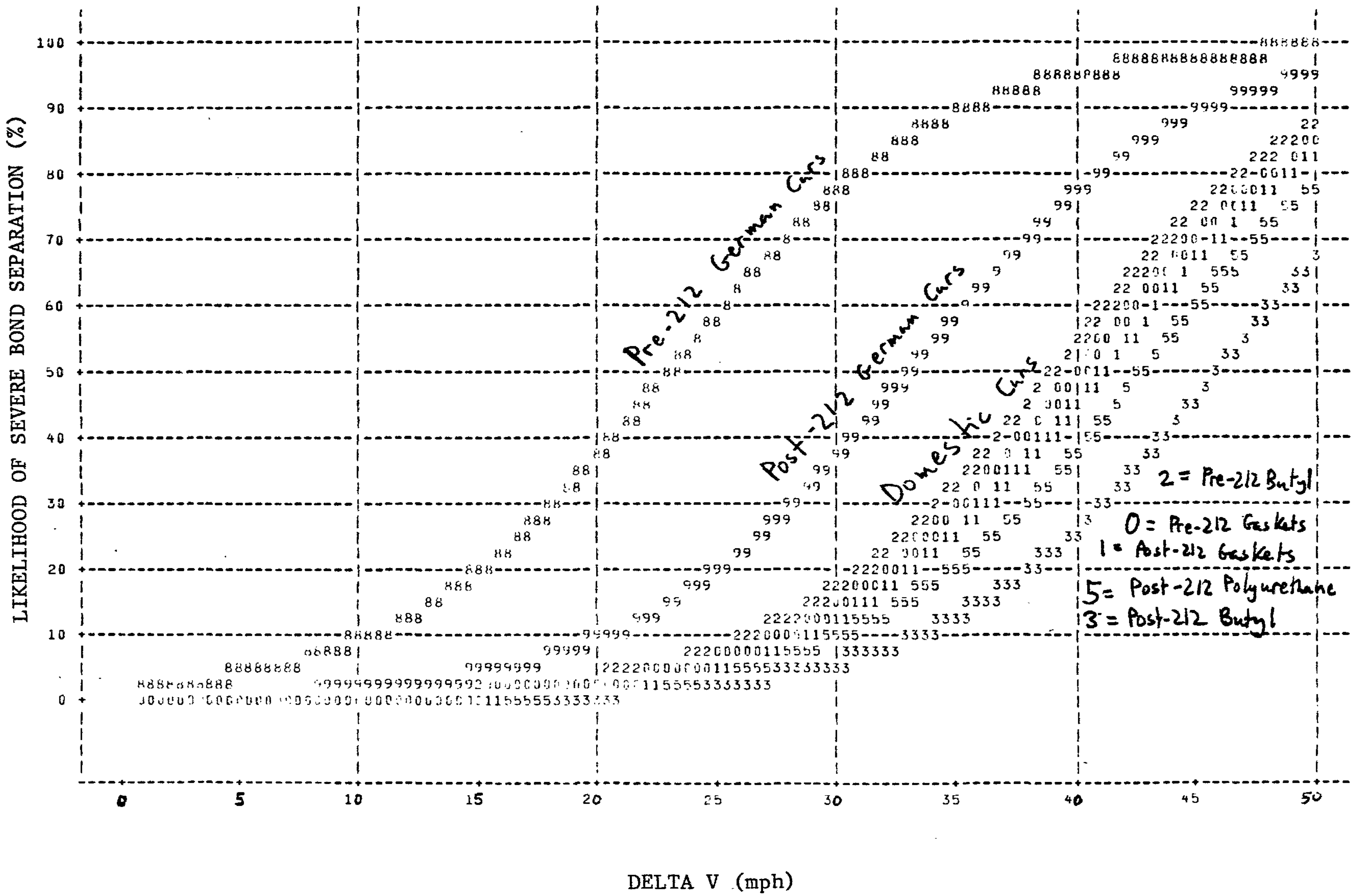
$$\log \frac{P\ (\text{sep.} > 50\%\ )}{1 - P\ (\text{sep.} > 50)}$$

as the dependent variable and the following regression coefficients and t-values for the independent variables:

Variable	Reg. Coefficient	t-Value
INTERCEPT	-7.026	
DV	.1754	15.83 (p < .05)
BUTYL	.190	0.42
URETHANE	-.295	-0.67
STD212	-.181	-0.34
BUTYL x STD212	-1.038	-1.67
GERMAN	2.987	2.76 (p < .05)
GERMAN x STD212	-1.582	-1.22

The t-values were generally smaller than those obtained in the regression on average amount of separation (Section 5.1.4) because the dependent variable used here is, by nature, less suitable for regression analysis. But the net results were approximately the same for both regressions: moderate differences between rubber gaskets and adhesive bonding on American cars; large differences between German and American cars. Figure 5-2 graphs the

FIGURE 5-2: SEPARATION OF MORE THAN HALF OF THE WINDSHIELD BOND, AS A FUNCTION OF DELTA V AND WINDSHIELD INSTALLATION METHOD, FRONTAL IMPACTS (NCSS LOGISTIC REGRESSION CURVES)



probability of severe bond separation as a function of windshield installation method and Standard 212 compliance, for American and German cars.

Table 5-7 shows the likelihood of severe bond separation in frontal 30 mph highway crashes--as predicted by the regression; it also shows the crash speeds at which there are 5, 10, 25 and 50 percent likelihoods, respectively, of severe bond separation.

Highway accidents appear to be a more hostile environment, as far as windshield retention is concerned, than staged crash tests. Whereas Standard 212 does not allow over a quarter of the bond to separate in a 30 mph laboratory test, 37 percent of the German cars that meet the standard lost more than half of the bond in 30 mph highway crashes. This was a dramatic improvement, nevertheless, over pre-standard German cars: 77 percent of them had severe bond separation in 30 mph crashes. All American cars, including those with pre-standard rubber gaskets, had substantially lower likelihood of losing half the bond than did the post-standard German cars. The differences among American cars (ranging from 6 to 17 percent) were much less than the difference between American and German cars.

It is interesting to note at what speeds cars have a 5 percent probability of severe bond separation--below those speeds, one might say that windshield retention is not a major safety issue. For American cars, that Delta V was 23 mph for pre-standard rubber gaskets and 28 mph for post-standard butyl tape. Those are speeds at which the unrestrained occupant has a moderate-to-high likelihood of serious injury even if not ejected from the vehicle. In pre-standard German cars, windshield retention became a problem at 6 mph--a speed at which unrestrained occupants are normally not seriously injured. Post-standard German cars raised that speed

TABLE 5-7

SEPARATION OF MORE THAN HALF OF THE WINDSHIELD BOND, AS A FUNCTION OF DELTA V AND WINDSHIELD INSTALLATION METHOD, FRONTAL IMPACTS (NCSS REGRESSION RESULTS)

Country	Windshield Installation Method	Pre/Post Standard 212	Percent of Cars with > 1/2 Sep. at 30 mph	Delta V at which > 1/2 Sep. Occurs on			
				5% of Cars	10% of Cars	25% of Cars	50% of Cars
United States	rubber gasket	pre	15	23	28	34	40
		post	12	24	29	35	41
	butyl tape	pre	17	22	27	33	39
		post	6	28	33	39	46
	polyurethane	post	10	25	30	36	43
Germany	rubber gasket	pre	77	6	11	17	23
		post	37	16	21	27	33

to 16 mph--a significant improvement, but still a speed at which an unrestrained occupant who remains within the vehicle should fare much better than an ejectee.

5.2 NCSS and MDAI data on ejection through the windshield portal

The NCSS file contains 46 cases of occupants of American or German cars who were completely or partially ejected through the windshield portal. The Multidisciplinary Accident Investigation (MDAI) file contains 65 such cases. When appropriately combined, the two files contain enough ejectees for statistically significant results on the effect of windshield installation methods on the risk of ejection. Sections 5.2.1-5.2.4 consider the effect of the windshield installation method on any type of ejection through the windshield portal (complete or partial). Section 5.2.5 looks at complete and partial ejection separately.

5.2.1 Effect of adhesive bonding on the risk of ejection

Four windshield installation methods are considered here: American cars with rubber gaskets, American cars with adhesive bonding, German cars (with rubber gaskets) before Standard 212 and German cars (with rubber gaskets) after Standard 212. The preceding analyses of bond separation--especially Table 5-5--showed no real differences between the two types of adhesive bonding (butyl tape and polyurethane sealant) or between pre- and post-Standard 212 American cars. Thus, the seven categories of installations considered in Tables 5-5, 5-6 and 5-7 have been reduced to four, in order to maximize sample size in each group.

Table 5-8 suggests that adhesive bonding very substantially reduced occupant ejection through the windshield portal in American cars. In NCSS, 13 of 3950 (unweighted) occupants were ejected through the windshield

TABLE 5-8

OCCUPANT EJECTION THROUGH THE WINDSHIELD PORTAL, BY WINDSHIELD INSTALLATION METHOD (NCSS AND MDAI DATA)

Windshield Installation Method	N of Occupants	n of Windshield Ejectees	Ejectees per 1000 Occupants	Reduction (%)
	NCSS* DATA ONLY			
United States/rubber gasket	3,950	13	3.29	55
United States/adhesive bonding	16,787	25	1.49	
Germany/pre-Standard 212 gasket	337	4	11.87	59
Germany/post-Standard 212 gasket	822	4	4.87	
	MDAI DATA ONLY			
United States/rubber gasket	2,455	26	10.59	74
United States/adhesive bonding	10,909	30	2.75	
Germany/pre-Standard 212 gasket	177	5	28.25	65
Germany/post-Standard 212 gasket	403	4	9.93	
	NCSS & MDAI COMBINED			
United States/rubber gasket	9,397**	39	4.15	68
United States/adhesive bonding	40,993**	55	1.34	
Germany/pre-Standard 212 gasket	730**	9	12.33	62
Germany/post-Standard 212 gasket	1,716**	8	4.66	

*Unweighted data

**In all, the MDAI data contain 65 windshield ejectees among 13,944 occupants. The NCSS data contain only 46 windshield ejectees among 21,896 occupants. To make the NCSS and MDAI samples comparable, each nonejected MDAI occupant case is counted (65/46) (21896/13944) = 2.219 times portal of American cars with rubber gaskets, a rate of 3.29 per 1000. The rate for cars with adhesive bonding was just 1.49 per 1000, a 55 percent reduction. (Table 5-8 is based on unweighted NCSS data and includes cars of all ages in order to maximize statistical precision at the cost of possible biases. A similar approach was used in the evaluation of Standard 214 [21], pp. 310-327). In the MDAI data, the ejection rate for adhesive bonding, at 2.75 per 1000, was 74 percent lower than the rate for rubber gaskets.

The most precise results are obtained by combining the two files. But how are they to be combined? Neither the unweighted NCSS nor MDAI are simple random samples of towaway accidents, so they need not be simply lumped together. Each file should be weighted according to the amount of "information" it supplies. Since MDAI has 65 windshield ejections and NCSS has only 46, MDAI contributes 65/46 as much information as NCSS. Since MDAI accomplishes this with only 13,944 occupant cases versus 21,896 for NCSS, each nonejected MDAI occupant ought to be counted (21,986/13,944)(65/46) = 2.219 times. Thus, the numbers in the "combined" section of Table 5-8 are obtained by simply adding the NCSS and MDAI ejectees while adding the NCSS N of occupants to 2.219 times the MDAI N of occupants. They show a 68 percent lower risk of windshield ejection in the cars with adhesive bonding than in domestic cars with rubber gaskets.

The preceding analysis may have been biased by factors such as vehicle age differences or anomalies of the MDAI sample. The results need to be checked by using another procedure that controls for such differences: the change in windshield ejections is measured relative to the change in ejections through other portals.

Table 5-9 indicates that 39 persons were ejected through the windshield portal in domestic cars with rubber gaskets on the combined NCSS and MDAI; 225 through other known portals. In the cars with adhesive

TABLE 5-9

OCCUPANT EJECTION: WINDSHIELD PORTAL RELATIVE TO OTHER PORTALS, BY WINDSHIELD INSTALLATION METHOD (NCSS AND MDAI DATA)

Windshield Installation Method	N of Ejectees: Windshield Portal	N of Ejectees: Other Known Portals	Relative Reduction of Windshield Ejection (%)
	NCSS DATA ONLY		
United States/rubber gasket	13	87	
United States/adhesive bonding	25	229	27
Germany/pre-Standard 212 gasket	4	16	
Germany/post-Standard 212 gasket	4	18	11
	MDAI DATA ONLY		
United States/rubber gasket	26	138	
United States/adhesive bonding	30	311	49
Germany/pre-Standard 212 gasket	5	29	
Germany/post-Standard 212 gasket	4	20	-16
	NCSS & MDAI COMBINED		
United States/rubber gasket	39	225	
United States/adhesive bonding	55	540	41*
Germany/pre-Standard 212 gasket	9	45	
Germany/post-Standard 212 gasket	8	38	-5

*Statistically significant reduction for adhesive bonding (Chi-square = 5.74, $p < .05$)

bonding, 55 were ejected through the windshield portal, 540 through other portals. This is a statistically significant 41 percent reduction in windshield ejection relative to other portals (Chi-square = 5.74, $p < .05$). The results for NCSS alone (27 percent) and MDAI alone (49 percent) are statistically compatible with the combined result. In fact, this may be too conservative an estimate of the effect of adhesive bonding: to the extent that a portion of the cars with rubber gaskets (especially on NCSS) were built before 1965 and did not have the improved door locks introduced in that year, the number of ejectees through other known portals is not a "pure" control group. Since the control group also experiences a modest reduction of risk, the reduction for test relative to control understates the "true" reduction in windshield ejections.

Based on the estimates in Tables 5-8 and 5-9, it is concluded that the effectiveness of adhesive bonding in reducing ejection through the windshield portal is roughly 50 percent. That reduction is entirely consistent with the decreases of bond separation found in Section 5.1--especially with the decreases in serious bond separation shown in Tables 5-6 and 5-7.

Incidentally, of the 111 persons ejected through the windshield portal, only 6 went through the glass--and 5 of these were in cars with pre-HPR windshields. The remaining 105 were ejected through the portal that opened when the windshield separated from its bond. The automated files do not indicate what caused the bond to separate--vehicle damage, occupant impact or both. A case-by-case study of NCSS by McKale, however, suggests that about a third of the ejectees traveled through empty space, the windshield having been completely removed from the frame by vehicle damage

[27], p. 38. About two-thirds at least made contact with the windshield on their way out and their impact may or may not have helped push the windshield out of the frame.

5.2.2 Effect of Standard 212 on ejection in German cars

Table 5-8 shows that the risk of ejection through the windshield portal in post-Standard 212 German cars on NCSS and MDAI (combined) was 62 percent lower than in the pre-standard cars. This very substantial reduction for Standard 212 in German cars is nearly the same as was found for adhesive bonding in American cars (68 percent). The results on ejection are consistent with the findings on bond separation, in that they show about the same (relative) effect for adhesive bonding in American cars as for Standard 212 in German cars.

It is not possible, however, to check the results for German cars in the same way as was done for American cars--i.e., by comparing windshield ejectees to ejections through other portals. This is because the door locks of Volkswagens were significantly modified in 1968 (just 2 years before the windshield), resulting in a dramatic reduction of ejection through doors, comparable to the improvement made in American cars in 1956 and far greater than the follow-up improvement made in 1965 domestic models [11]. As Table 5-9 shows, ejections through other portals (primarily doors) decreased even faster than windshield ejections in German cars.

It is interesting to look at the results on serious bond separation (Table 5-6) and ejection (Table 5-8) side by side:

	Pct. of Cars with > 1/2 Bond Sep.	Windshield Ejectees per 1000 Occupants
U.S./rubber gasket	3.6	4.2
U.S./adhesive bonding	1.9	1.3
German/pre-Std. 212 gasket	25.4	12.3
German/post-Std. 212 gasket	11.5	4.7

(The percentages of American cars with greater than half of the bond separated are averages of the "all speeds" data in Table 5-6, weighted by the sample sizes in the lower half of the table.) American cars show approximately a 50 percent reduction in serious bond separation and ejection associated with adhesive bonding. German cars show a 50 percent reduction of bond separation and ejection for Standard 212.

The only inconsistency is in the absolute sizes of the numbers. For the American cars, the bond separation rates (per 100 weighted cars) and ejection rates (per 1000 unweighted occupants) are of about the same magnitude (4 for rubber gaskets, less than 2 for adhesive bonding). In the German cars, the bond separation rate is 6 times as high as in comparable American cars (i.e., pre-Standard 212 vs. U.S. gaskets, post-Standard 212 vs. U.S. adhesive bonding) but the ejection rate is only 3 times as high. In other words, the windshield ejection rate in German cars is only half as large as would be expected on the basis of their windshield retention performance. The reason, undoubtedly, is that German cars sold in the United States (before 1975)--most of which were Volkswagen Beetles--had substantially smaller windshields than American cars and/or a more protruding instrument panel that would be likely to hold the occupant's knees; both factors would reduce the likelihood of ejection through the windshield portal. Indeed, Rodloff and Breitenbuerger claimed these design factors minimized the risk of windshield ejection in German cars and obviated the need for a rigid bonding method [44]. But the NCSS and MDAI data show that the risk of windshield ejection in pre-Standard 212 German cars, although not as extreme as the bond separation problem, was nevertheless 3 times as high as in American cars. Even in post-Standard 212 German cars the ejection risk, although substantially reduced, is likely to have been higher than in the American cars with rubber gaskets.

5.2.3 Injury sources of ejectees

The preceding section gave strong evidence that tighter bonding methods reduced the risk of ejection through the windshield portal. But how many of those ejectees received their most serious injuries from items they contacted while they were still within the passenger compartment and, as a result, would not have experienced a reduction in overall injury severity even if their ejection could have been prevented?

Table 5-10 shows that the windshield portal is significantly different from other ejection portals in that only 32 percent of the windshield ejection fatalities received their fatal lesions exclusively after they had left the passenger compartment--as opposed to 57 percent of the ejectees through other portals. These percentages are based on combined NCSS and MDAI data: a sample of 22 persons ejected through the windshield

TABLE 5-10

INJURY SOURCES OF EJECTEES

Injury Severity	Data Source	N of Ejectees with Most Severe Injury (s): Primarily Outside of Car	Partly/Wholly Inside of Car	Unknown Unclear	Percent-Exterior to Passenger Compartment
		WINDSHIELD PORTAL EJECTEES			
Fatal	NCSS	0	1	8	
	MDAI	7	14	6	
	NCSS & MDAI	7	15		32*
AIS 3-5 Nonfatal	NCSS	3	15	18	
	MDAI	7	8	4	
	NCSS & MDAI	10	23		30
ALL OF THE ABOVE		17	38		31
		EJECTIONS THROUGH OTHER PORTALS			
Fatal	NCSS	23	17	68	
	MDAI	105	79	37	
	NCSS & MDAI	128	96		57*

*Significantly fewer windshield ejectees are killed by contacts outside the car than nonwindshield ejectees (Chi-square = 4.34, $p < .05$)

with clearly documented fatal lesions, 224 through other portals. Despite the small samples, the differences in the distribution of injury sources are statistically significant (Chi-square = 4.34, $p < .05$).

In addition, NCSS and MDAI contain 33 cases of persons ejected through the windshield who received nonfatal AIS 3-5 injuries: 30 percent of them received their most severe injury(s) after being ejected (almost the same percentage as for the fatals). When the fatals and AIS 3-5 injuries are combined, 31 percent of the windshield ejectees received their most severe lesion(s) after being ejected.

In other words, out of every 10 persons who were ejected through the windshield portal and killed, about 7 died as a result of injuries sustained within the passenger compartment and presumably would still have died even if an improved windshield bonding technique had prevented their ejection.

Why are windshield ejectees so much more likely to have been killed by interior contacts than are the ejectees through other portals such as the door? On the one hand, the windshield portal is a fairly small opening (from top to bottom) and is surrounded by solid structures such as the instrument panel, steering assembly and header. Occupants are likely to contact these surfaces on their way out through the windshield portal. By contrast, when a door opens, there is little to impede the occupant's exit through that area. These considerations maximize risk of injury inside the vehicle for windshield ejectees. At the same time, vehicle dynamics in typical rollovers generally would not cause a windshield ejectee's car to roll over him; in nonrollover cases, the windshield ejectee may end up on the car's hood where he is sometimes protected from being crushed between his own vehicle and the other vehicle or fixed object. By contrast, a person ejected through an open door is highly vulnerable to being pinned between his own vehicle and the ground, another vehicle, or a fixed object. These considerations minimize risk of injury outside the vehicle for windshield ejectees.

Thus, even though adhesive bonding and Standard 212 reduced windshield ejection by about 50 percent in American and German cars, respectively, the modifications only saved .3 x .5 = 15 percent of the windshield ejection fatalities and serious injuries--still an impressive reduction for such a relatively minor vehicle modification.

5.2.4 Ejection portals by crash mode

Table 5-11 shows that the windshield portal accounted for 105 out of the 831 ejectees on NCSS and MDAI whose portals were known--i.e., 11 percent of the ejectees. NCSS and MDAI are very consistent with one another: 11 percent on NCSS, 12 percent on MDAI. It is not surprising that the windshield is a common portal for persons ejected in frontal crashes: 17 percent of frontal ejections were through the windshield portal. But 16 percent of ejectees in rollover crashes also went through the windshield portal. In fact, close to half of all windshield ejections occurred in rollovers. Perhaps, in rollovers, the occupants are lifted away from the instrument panel and steering column (which impede windshield ejection) while exterior damage to the top of the car may help dislodge the windshield and open an ejection portal. But in side and rear impacts the windshield portal accounts for only 5 percent of ejections, significantly fewer than in frontals and rollovers (Chi-square = 29.34, $p < .05$).

The preceding statistics were based on cars of all model years, including those with adhesive bonding. For problem identification purposes, however, it is necessary to focus on the cars that predated the safety improvements. Table 5-12 shows that in American cars with rubber gaskets

TABLE 5-11

OCCUPANT EJECTION PORTALS BY CRASH MODE
(NCSS AND MDAI DATA)

Primary Vehicle Damage Site	N of Ejectees: Windshield Portal	N of Ejectees: Other Known Portals	Percent of Ejectees thru Windshield Portal
NCSS DATA ONLY			
Frontal	20	86	19
Rollover	11	74	13
Frontal or rollover	31	160	16
Side or back	9	173	5
ALL IMPACTS	40	333	11
MDAI DATA ONLY			
Frontal	19	108	15
Rollover	34	165	17
Frontal or rollover	53	273	16
Side or back	12	225	5
ALL IMPACTS	65	498	12
NCSS & MDAI COMBINED			
Frontal	39	194	17
Rollover	45	239	16
Frontal or rollover	84	433	16*
Side or back	21	398	5*
ALL IMPACTS	105	831	11

*Significantly more windshield ejections in frontals/rollover than in side rear impacts (Chi-Square = 29.34, $p < .05$)

the windshield portal was especially prevalent, accounting for 15 percent of all ejectees and 22 percent of the ejectees in frontals and rollovers. In German cars, prior to Standard 212, the windshield portal was even more common, accounting for 17 percent of all ejections and 30 percent of ejectees in frontals and rollovers.

Section 5.3 analyzes ejections in FARS data. Since FARS does not identify the ejection portal, it has to be based on overall ejection risk. The analyses are based on frontals and rollovers where, as shown above, the effect of windshield bonding modifications is likely to be seen. If adhesive bonding really reduces windshield ejection by 50 percent, it should reduce overall ejection risk by about 11 percent in frontals and rollovers on FARS (since Table 5-12 indicates that 22 percent of ejections in frontals and rollovers involving domestic cars with rubber gaskets are through the windshield portal). If Standard 212 really reduced windshield ejection by 50 percent in German cars, it should reduce overall ejection risk by about 15 percent in frontals and rollovers on FARS.

If, moreover, FARS is analyzed by comparing ejected to nonejected persons, the observed "effectiveness" results should be even higher than 11 and 15 percent, respectively, because, according to Section 5.2.3, a large percentage of the persons who had been ejected and killed would now remain inside the vehicle and die: the nonejected fatalities would not be a "clean" control group but should increase in number.

TABLE 5-12

OCCUPANT EJECTION PORTALS BY CRASH MODE
AND WINDSHIELD INSTALLATION METHOD
(NCSS AND MDAI DATA, COMBINED)

Primary Vehicle Damage Site	N of Ejectees: Windshield Portal	N of Ejectees: Other Known Portals	Percent of Ejectees thru Windshield Portal
DOMESTIC CARS WITH RUBBER GASKETS			
Frontal	15	54	22
Rollover	17	61	22
Frontal or rollover	32	115	22
Side or back	6	106	5
ALL IMPACTS	38	221	15
PRE-STANDARD 212 GERMAN CARS WITH RUBBER GASKETS			
Frontal	5	11	31
Rollover	3	8	27
Frontal or rollover	8	19	30
Side or back	1	25	4
ALL IMPACTS	9	44	17

5.2.5 Complete vs. partial ejection

Adhesive bonding appears to be about equally effective in reducing the risk of "complete" or "partial" occupant ejection through the windshield portal. The following tabulation of NCSS and MDAI data shows that the number of persons completely ejected through the windshield, per 1000 crash-involved occupants, decreased by 63 percent; the rate of partial ejection, by 74 percent:

	N of Occupants	n of Windshield Ejectees	Ejectees per 1000 Occ.	Reduction (%)
COMPLETE EJECTION				
Rubber gaskets	9,397	23	2.45	
Adhesive bonding	40,993	37	0.90	63
PARTIAL EJECTION				
Rubber gaskets	9,397	16	1.70	
Adhesive bonding	40,993	18	0.44	74

There was no significant difference between rubber gaskets and adhesive bonding in the distribution of complete vs. partial ejection (Chi-square = 0.68, $p > .05$)

Proper interpretation of these results requires an explanation of how field accident investigators define "complete" and "partial" ejection in actual practice. Complete ejection, of course, means that the occupant leaves the passenger compartment entirely. Partial ejection, in theory, could include someone for whom any part of the body extended outside the boundaries of the compartment at any time in the crash sequence. In actual practice, though, it is limited to persons who had a substantial part of their body outside the compartment at the end of the crash sequence or who had evident injury-producing contacts with exterior objects. Specifically, persons whose heads broke and penetrated the windshield (the customary situation before HPR) would not normally be coded as "partially ejected" in NCSS or MDAI (comments by Roberts and Franklin of the NHTSA Accident Investigation Division). Thus, in the way that the terms are used by investigators, there is relatively little difference between "partial" and "complete" ejection--it is not surprising, as a result, that adhesive bonding had about the same effect on both types.

5.3 FARS data on ejection

Since approximately 23 percent of car occupant fatalities are ejectees, the Fatal Accident Report System contains over 40,000 ejection cases (i.e., 5000 deaths per year)--incomparably more than other files. Of course, the data do not identify the ejection portal. One analysis technique is to compare ejection fatalities to nonejection fatalities in frontal and rollover crashes (the types where windshield ejection is most likely--see Section 5.2.4). It will clearly show that tighter windshield bonding has reduced ejection but will not clarify how many of the persons whose ejection was prevented sustained fatal lesions from interior contacts. The second technique is to calculate ejection and nonejection fatality rates per million vehicle years. Unfortunately, there were too many confounding factors in the data for this approach to produce clear-cut results. Both techniques are explained in Chapter 3.

Since FARS does not identify the ejection portal, it is essential to remove from the analysis the effects of safety modifications which may have reduced ejection through portals other than the windshield--viz., the improvements made to door locks in domestic cars (1965) and Volkswagens (1968). Therefore, in the analyses of domestic cars, all pre-1965 models are removed as well as "corresponding" post-1964 model years. For example, models that received adhesive bonding in 1965 (Chevrolet Impala) are excluded entirely from the analysis: since all pre-1965 cars had to be excluded (old-style door locks) the inclusion of any post-1964 cars would cause an unbalanced sample (all adhesive bonding and no rubber gaskets). For models that received adhesive bonding in 1966 (Ford Fairlane), only model years 1965 and 1966 are included in the analysis: a balanced sample of one model year with gaskets and one year with adhesive bonding. For models that received adhesive bonding in 1967 (AMC Ambassador), only model years 1965-68 fare included in the analysis, etc. As for Volkswagens, the analyses are limited to model years 1968-71 (2 years with improved door locks and pre-Standard 212 gaskets vs. 2 years with improved door locks and post-Standard 212 gaskets). German cars other than Volkswagen are excluded from the FARS analysis since the exact installation dates of the relevant safety modifications were unknown--and exact dates are of much greater importance in analyzing FARS than NCSS or MDAI.

5.3.1 Effect of adhesive bonding

Table 5-13 clearly shows that adhesive bonding reduced the risk of fatal ejection, relative to nonejection fatalities, in domestic cars with frontal or top damage. There were 542 ejection fatalities in cars of the last model year with rubber gaskets. Based on the nonejection fatality ratio, 542 (2107/1517) = 753 ejection fatalities would be expected in cars of the first model year with adhesive bonding. In fact, only 665 occurred. This is a 12 percent reduction of ejection relative to nonejection fatalities and it is statistically significant (Chi-square = 3.43, one-sided

TABLE 5-13

FARS 1975-82: EJECTED VS. NONEJECTED FRONT-SEAT OCCUPANT FATALITIES, BY WINDSHIELD INSTALLATION METHOD, POST-1964 DOMESTIC CARS WITH FRONTAL OR TOP DAMAGE

Model Years	N of Fatalities		Ejection Reduction for Adhesive Bonding (%)	Chi-Square
	Ejected	Not Ejected		
Last MY w. rubber gaskets	542	1517		
First MY w. adhesive bonding	665	2107	12	3.43*
Last 2 w. rubber gaskets	1153	3156		
First 2 w. adhesive bonding	1161	3739	15	11.44*
Last 3 w. rubber gaskets	1621	4566		
First 3 w. adhesive bonding	1572	5107	13	12.21*
Last 4 w. rubber gaskets	2090	5708		
First 4 w. adhesive bonding	1861	6149	17	26.84*

*Significant reduction of ejections relative to nonejected occupants (one-sided $p < 05$).

$p < .05$). When the sample is extended to include the second year before and after the transition to adhesive bonding, the reduction is a slightly larger 15 percent, but it drops back to 13 percent in the $\pm$ 3-year comparison. The sequence of ejection reduction estimates--12, 15, 13, 17--shows, at most, a modest upward trend but indicates a clear effect for adhesive bonding on the order of 12-14 percent.

How does this effect compare to the NCSS and MDAI findings (Section 5.2) that adhesive bonding reduced overall ejection risk in frontals and rollovers by 11 percent, but that about 70 percent of the persons who were saved from ejection would not have experienced a reduction in their overall injury level? Table 5-13 consistently shows 2.75 times as many nonejection as ejection fatalities in cars with gaskets. If the above 11 and 70 percent figures from NCSS/MDAI are valid, the expected effect in FARS would be

$$1 - \frac{\text{ejected, adhesive}}{\text{ejected, gasket}} \times \frac{\text{nonejected, gasket}}{\text{nonejected, adhesive}}$$

$$= 1 - \frac{1 - .11}{1} \quad \frac{2.75}{2.75 + (.7)\,(.11)} = 13.4\%$$

which is almost exactly what was actually found in FARS.

Although the FARS effect is certainly consistent with NCSS and MDAI, it is still not clear whether the observed relative effect is primarily due to a reduction of ejection or an increase of nonejection. Table 5-14 shows the absolute effects: the rates of ejection, nonejection and total fatalities per million vehicle years. Unfortunately, few conclusions can be drawn from the table. Clearly, there is a confounding

TABLE 5-14

FARS 1975-82: EJECTED VS. NONEJECTED FRONT-SEAT OCCUPANT FATALITIES IN FRONTAL CRASHES AND ROLLOVERS, PER MILLION EXPOSURE YEARS ADHESIVE BONDING VERSUS RUBBER GASKETS, POST-1964 DOMESTIC CARS

Model Years	Car Exposure Years (Millions)	Ejectees			Nonejectees			All Fatalities		
		N	Rate	% Red.	N	Rate	% Red.	N	Rate	% Red.
Last MY w. rubber gaskets	13.42	542	40.39		1517	113.04		2059	153.42	
First MY w. adhesive bonding	17.12	665	38.84	4	2107	123.07	-9	2772	161.92	-6
Last 2 w. rubber gaskets	27.78	1153	41.50		3156	113.61		4309	155.11	
First 2 w. adhesive bonding	31.84	1161	36.46	12	3739	117.43	-3	4900	153.89	1
Last 3 w. rubber gaskets	39.94	1621	40.58		4566	114.32		6187	154.91	
First 3 w. adhesive bonding	44.79	1572	35.09	14	5107	114.02	0	6679	149.12	4
Last 4 w. rubber gaskets	49.87	2090	41.91		5708	114.46		7798	156.37	
First 4 w. adhesive bonding	55.05	1861	33.81	19	6149	111.70	2	8010	145.50	7

factor in the $\pm$ 1 model year comparison, where there is an unreasonably large 6 percent increase in the overall fatality rate. The best explanation would appear to be that the transition to adhesive bonding usually coincided with a major body restyling. It is likely that cars of the first year of a restyling were driven more heavily than cars of other model years and, as a result, may have had higher fatality rates per million exposure years. The results for the $\pm$2 model year comparison are almost exactly what would be expected from NCSS/MDAI--a 12 percent decrease in ejectees, a 3 percent increase in nonejectees and a 1 percent overall reduction in the fatality rate--but this is probably a lucky coincidence. The results for $\pm$3 and $\pm$4 model years begin to show even higher reductions of ejection and zero or slightly positive effects on nonejection, probably indicating a trend to lower fatality rates in newer cars. In short, the results are certainly compatible with an 11 percent reduction of ejections, partly offset by an increase in nonejections, yielding a far more modest overall fatality reduction. But sampling errors, trends and confounding factors make it impossible to pin down the estimate to the nearest percent--and that is the level of accuracy needed in the case of nonejections, since the effect under consideration is at most a few percent. It is also pointless to attempt a regression analysis since it will only control for the age-related trend but not the one-time confounding factor in the first model year with adhesive bonding.

In short, the FARS analyses strongly confirm the NCSS/MDAI findings that adhesive bonding reduced ejections by 11 percent but they do not give a clear indication how many of the persons whose ejection was prevented died from injuries sustained inside the vehicle. It will be necessary to rely on the NCSS/MDAI estimate that 70 percent of them died of those injuries (Section 5.2.3).

One additional word of caution is needed. Table 5-11 showed that the windshield portal is far more relevant among ejectees in frontals and rollovers than in side impacts. It might be thought that a good way to analyze FARS is to measure the change in frontal and rollover ejectees relative to side impact ejectees. But in FARS, when the crash mode is based on the "principal impact point," there was almost as great a reduction in side impact ejections as in frontals and rollovers. This is probably because many rollovers (with side damage) and frontals (with spillover damage to the side) are classified on FARS as having the principal impact point on the side--but it could also indicate the presence of other confounding factors.

5.3.2 Effect of Standard 212 in Volkswagens

Table 5-15 clearly shows that occupants of Volkswagens meeting Standard 212 had a lower risk of fatal ejection, relative to fatal nonejection, than did occupants of pre-Standard 212 Volkswagens. In 1970-71 Volkswagens involved in frontals and rollovers, there were relatively 22 percent fewer ejections than in 1968-69 Volkswagens, a statistically significant reduction (Chi-square = 7.48, $p < .05$). In the ± 1 model year comparison, the reduction was virtually the same, 17 percent, although not quite statistically significant. As mentioned earlier, the analysis is limited to post-1967 cars--all of which have improved door locks and energy-absorbing steering columns--in order to avoid confounding effects of other safety devices. The results are compatible with NCSS/MDAI findings that Standard 212 reduced overall ejection risk in VW frontals and rollovers by 15 percent. If 70 percent of the persons saved from ejection died from

TABLE 5-15

FARS 1975-82: EJECTED AND NONEJECTED FRONT-SEAT OCCUPANT FATALITIES IN VOLKSWAGENS WITH FRONTAL OR TOP DAMAGE, BY STANDARD 212 COMPLIANCE

Model Years	Volkswagen Fatalities: Ejected	Volkswagen Fatalities: Not Ejected	Ejection Reduction for Std. 212 (%)	Chi-Square
1969 (last yr. before Std. 212)	147	507		
1970 (first yr. after Std. 212)	127	530	17	1.96
1968-69	306	968		
1970-71	283	1155	22	7.48*

*Significant reduction of ejections relative to nonejected occupants ($p < .05$)

injuries with interior contacts and if nonejection fatalities were 3.2 times as numerous as ejection fatalities, prior to Standard 212, the expected effect in FARS would be

$$1 - \frac{\text{ejected, post}}{\text{ejected, pre}} \qquad \frac{\text{nonejected, pre}}{\text{nonejected, post}}$$

$$= 1 - \frac{1 - .15}{1} \qquad \frac{3.2}{3.2 \; + (.7)\;(.15)} = 18\%$$

which corresponds nicely to what was found in FARS.

Table 5-16 shows the rates of ejection, nonejection and total fatalities per "million vehicle years." They show a 10-14 percent drop in the overall fatality rate which is surely unrelated to Standard 212. A possible explanation may be found in the way "exposure years" were calculated for this report (Section 3.5): model year sales were multiplied by an age-related survival factor which was the same for American and foreign cars. If Volkswagens are retired more slowly than the average car, the exposure of the older cars is understated and the fatality rates overstated.

TABLE 5-16

FARS 1975-82: EJECTED AND NONEJECTED FRONT-SEAT OCCUPANT FATALITIES IN VOLKSWAGENS WITH FRONTAL OR TOP DAMAGE, PER MILLION EXPOSURE YEARS, BY STANDARD 212 COMPLIANCE

Model Year	Volkswagen Exposure Years (millions)	Volkswagen Fatalities	Fatality Rate	Reduction for Post-Standard Cars (%)
		EJECTEES		
1969 (last yr. before Std. 212)	2,683	147	54.79	
1970 (first yr. after Std. 212)	3,137	127	40.48	26
1968-69	5,052	306	60.57	
1970-71	6,324	283	44.75	26
		FATALITIES WHO WERE NOT EJECTED		
1969	2,683	507	188.97	
1970	3,137	530	168.95	11
1968-69	5,052	968	191.61	
1970-71	6,324	1155	182.64	5
		ALL FATALITIES		
1969	2,683	654	243.76	
1970	3,137	657	209.44	14
1968-69	5,052	1274	252.18	
1970-71	6,324	1438	227.39	10

At the risk of "comparing apples to oranges", it is interesting to tabulate the ejection fatality rates of American cars and Volkswagens, based on averages of the numbers in Tables 5-14 and 5-16:

	Ejection Fatalities per Million Vehicle Years (Frontal + Rollover)
U.S./rubber gasket	41
U.S./adhesive bonding	37
Volkswagen/pre-Std. 212 gasket	55
Volkswagen/post-Std. 212 gasket	45

Despite the differences of the cars, problems with exposure measurement, etc., it is remarkable how close the American cars' ejection rates are to those for VW. Standard 212 helped reduce the ejection rate in VW's substantially, to the point where it was comparable to that of American cars with rubber gaskets. But prior to Standard 212, ejection risk was clearly higher in VW's than in domestic cars. The absolute reduction in the ejection rate was twice as high in the VW's as in the American cars--just like what was found in NCSS and MDAI.

5.4 Summary: "best" estimates of effectiveness and their confidence bounds

NCSS analyses clearly showed that adhesive bonding improved windshield retention in American cars. So did the clips used to secure the rubber gasket to the frame in Volkswagens. Analyses of NCSS/MDAI and FARS showed reductions of occupant ejection commensurate with the reduction of windshield bond separation in crashes. It is, above all, the close agreement between the bond separation and ejection statistics as well as the consistency between NCSS/MDAI and FARS that enhances the credibility of the effectiveness estimates.

o Effect of adhesive bonding on windshield separation: the NCSS analysis of amounts of bond separation suggested a 32-35 percent reduction took place initially after the implementation of adhesive bonding (Table 5-1). This would appear to be an underestimate of the long-term benefits of bonding because the initial adhesive bonding method used by GM was looser than their subsequent applications (see Tables 5-2 and 5-4). While GM's initial adhesive bonding technique reduced bond separation by only 19 percent relative to rubber gaskets, later applications by GM had close to a 50 percent reduction. The NCSS analyses of serious bond separation (Table 5-6) showed, on the average, a 48 percent reduction for adhesive bonding. When that number is rounded to 50 percent, it is the "best" estimate of reduction in bond separation and it is consistent with the reductions found in GM cars of the early 1970's as well as in Ford and Chrysler products. Since this is an "engineering" statistic which is not directly used to calculate benefits, confidence bounds will not be calculated but it should be noted that every analysis in Section 5.1 found the effect of adhesive bonding to be statistically significant.

o Effect of Standard 212 on bond separation in German windshields: the NCSS analysis of amounts of bond separation indicated a 51 percent reduction in German cars subsequent to Standard 212 (Table 5-3). The analysis of the probability of serious bond separation indicated a 55 percent reduction (Table 5-6). When these numbers are rounded to 50 percent, they serve as the "best" estimate. The regression of bond separation as a function of Delta V clearly associated a statistically significant reduction with Standard 212 in German cars (Section 5.1.4).

o Effect of adhesive bonding on ejection through the windshield portal: two analyses of NCSS/MDAI data were performed (Section 5.2.1). A simple comparison of ejection rates yielded a 68 percent reduction, thought to be an overestimate; a comparison with ejections through other portals showed a 41 percent reduction, shown likely to be a moderate underestimate. The best estimate would appear to be 50 percent since the latter of the two preceding numbers is thought to be closer to the right answer. A 50 percent estimate is also strongly supported by the FARS results (Section 5.4.1) and, of course, the analyses of bond separation. For a rough idea of the sampling error, it should be noted that there were 39 windshield ejectees in domestic cars with rubber gaskets and 55, with adhesive bonding. Since

$$s = (1 -.5)\ (1/39 + 1/55)^{1/2} = 10 \text{ percent}$$

it is reasonable to talk in terms of confidence bounds on the order of E ± 1.645 s or 34 to 66 percent. These relatively narrow confidence bounds can be accepted without undue fear of nonsampling error, etc., because the FARS results so strongly support the NCSS/MDAI findings. Moreover, Section 5.2.5 suggested that the effects on complete and partial ejection were about equal.

o Life-saving effectiveness of adhesive bonding, for persons ejected through the windshield portal: while adhesive bonding will prevent about 50 percent of the ejections through the windshield portal, it was shown in Section 5.2.3 that about 70 percent of these persons would not experience a reduction in their overall injury severity, because their most severe lesions(s) had been sustained inside the passenger compartment. Thus, only .3 x .5 = 15 percent of the fatalities and serious injuries would actually be eliminated. The statistic quoted from Section 5.2.3 is based on a sample of 55 NCSS and MDAI cases and has sampling error

$$s_1 = (pq/n)^{1/2} = .06$$

The sampling error for the 15 percent life-saving effectiveness estimate, which is based on the product of two independent variables, is approximately

$$s_2 = .15\ [(s/.5)^2 + (s_1/.3)^2]^{1/2} = .04$$

Because of uncertainties about possible biases in the data on injury-producing contact points used in Section 5.2.3 and the unavailability of FARS or other data to confirm that NCSS/MDAI finding, it is recommended that wider-than-usual confidence bounds be used, such as $E \pm 1.96\ s$, or 7 to 22 percent.

o Life-saving effectiveness of Standard 212 in German cars: the analyses of the effect of Standard 212 on ejection in German cars (Sections 5.2.2 and 5.3.2) had results that were nearly equal to those for adhesive bonding in domestic cars, with the same level of statistical significance in the FARS analyses. Moreover the correspondence between the reductions of bond separation and ejection appears to hold equally well in American and German cars. It is concluded that the best estimate of the effect of Standard 212 on ejection in German cars is equal to the effect of adhesive bonding in American cars: a 50 percent reduction in the risk of ejection through the windshield portal and the saving of 15 percent of the deaths and serious injuries of windshield ejectees. It is appropriate, however, to widen the confidence bounds for the latter estimate to 5-25 percent, because of additional uncertainty as to whether the contact point distributions in NCSS/MDAI, which are based mainly on domestic cars, are reasonable for German cars such as Volkswagens.

CHAPTER 6

THE EFFECT OF WINDSHIELD INSTALLATION METHOD ON THE INJURY RISK OF OCCUPANTS WHO ARE NOT EJECTED

The preceding chapter showed that tighter windshield installation methods are effective in reducing the risk of occupant ejection through the windshield portal. The vast majority of occupants, however, are not ejected in crashes. Rodloff, Breitenbuerger and Fargo, among others, raised concern that tight windshield installations significantly increase the injury risk of persons who are not ejected (see Sections 2.2 and 2.3.1). The mechanisms they suggested for increased injury risk were:

o The lack of give or pullout in the periphery could cause occupants to break and penetrate the windshield at lower speeds, resulting in a higher risk of serious lacerations and facial fractures.

o When the windshield's interlayer remains intact, the lack of energy-absorption by the periphery could increase blunt impact forces when an occupant strikes the windshield.

The analyses of NCSS, New York and Texas accident data of this chapter, however, refute those hypotheses and strongly confirm Trosien and Patrick's laboratory studies which indicated that the windshield installation method had little effect on windshield performance (see Sections 2.2.2 and 2.2.3). To begin with, the NCSS data do not show that tighter windshield installation methods significantly increase the probability of windshield penetration in highway accidents. The New York data shows that adhesive bonding did not increase the risk of any type of injury--lacerative or blunt-impact--in cars with HPR windshields. NCSS and Texas data confirm this finding. Even in Volkswagens, where Standard 212 resulted in a tightening of windshield installations far more dramatic than the effect of adhesive bonding in American cars (see Section 5.1), injury risk did not increase. Only in cars with pre-HPR windshields does the New York data suggest that adhesive bonding may have increased injury risk, consistent with Fargo's results which were also based on pre-HPR glazing. But the New York results are not confirmed by Texas data, in this case.

The procedures and definitions for this chapter's analyses were set forth in Chapter 3. The analyses themselves closely parallel those of Chapter 4, except that windshield installation method (rubber gaskets vs. adhesive bonding in domestic HPR cars; gaskets vs. adhesive in domestic pre-HPR cars; pre- vs. post-Standard 212 Volkswagens) is the variable of interest here while the glazing method (pre-HPR vs. HPR) was studied in Chapter 4.

6.1 NCSS data on windshield penetration in accidents

In Section 4.2, it was shown that HPR windshields reduced the likelihood of an occupant breaking and penetrating the windshield by 78 percent in highway accidents. (The probability of "penetration" was measured by restricting the data to occupants who were known to have contacted the windshield and finding the percentage whose "occupant contact broke the windshield"--see Section 3.2.) Rodloff and Breitenbuerger feared that rigid bonding of the windshield "defeats a great part of the improvements achieved [44]" by the HPR windshield in reducing penetration.

But Table 6-1 (which is based on unweighted NCSS data to minimize sampling error--a necessary step in view of the small samples of pre-HPR and German cars) does not show any disadvantage for the more rigid mounting techniques in American highway accidents. In domestic cars with HPR windshields, 19.5 percent of the occupants penetrated the windshield if it was attached with a rubber gasket; 19.4 percent if it was adhesively bonded--essentially no change at all. In domestic cars with pre-HPR windshields, 57 percent penetrated windshields attached by gaskets; 53 percent broke adhesively bonded windshields--a nonsignificant difference which is, moreover, in the "wrong" direction. Certainly adhesive bonding did not defeat a great part--or even any part--of the benefits of HPR.

But even in German cars, which had close to a true "pop-out" windshield prior to Standard 212, the much tighter bonding used to gain compliance with the standard seemed to have little effect on the vulnerability of the windshield. Table 6-1 shows that 20 percent of the occupants penetrated the pre-Standard 212 windshields--again, a change in the "wrong" direction. Moreover, the penetration rates are nearly the same as for domestic cars with HPR windshields. Thus, it appears to be the type of glazing that counts, not the type of bonding.

Table 6-2 shows the likelihood of penetration as a function of Delta V. It provides data points for a regression of the probability of penetration as a function of Delta V, type of glazing and windshield installation method. The table is based on weighted NCSS data, so it can be compared directly to Table 4-13 (which subdivided the data by type of glazing but not windshield installation method). German cars are excluded because there are far too few of them in NCSS for a meaningful analysis of

TABLE 6-1

WINDSHIELD PENETRATION BY WINDSHIELD INSTALLATION METHOD AND TYPE OF GLAZING, FRONT-SEAT OCCUPANTS IN FRONTAL CRASHES WITH WINDSHIELD CONTACT INJURIES (UNWEIGHTED NCSS DATA)

Windshield Installation Method	N of Persons	Percent who Penetrated Windshield	Change (%)
	AMERICAN CARS - HPR WINDSHIELDS		
Rubber gasket	195	19.5	
Adhesive bonding	1264	19.4	1 reduction
	AMERICAN CARS - PRE-HPR WINDSHIELDS		
Rubber gasket	87	57	
Adhesive bonding	30	53	7 reduction
	GERMAN CARS - HPR WINDSHIELDS		
Pre-Std. 212 gasket	25	20	
Post-Std. 212 gasket	93	16	19 reduction

penetration by Delta V. Table 6-2 shows a vast difference between HPR and pre-HPR glazing but no obvious difference between rubber gaskets and adhesive bonding, other than random fluctuations in the cell entries due to their small sample sizes.

A simple logistic regression model, containing only the main effects, fit the data well (R^2 = .634, df = 23) and yielded the following equation (see also Section 3.9.2):

$$P\ (\text{penetration}) = \frac{\exp\ (-2.68 + 0.186\ DV - 3.51\ HPR + 0.06\ ADHESIVE)}{1 + \exp\ (-2.68 + 0.186\ DV - 3.51\ HPR + 0.06\ ADHESIVE)}$$

This is a statistically significant reduction in penetration for HPR (F = 8.71; df = 1,23; $p < .05$) and a trivial increase for adhesive bonding which is not statistically significant (F = 0.01; df = 1,23; $p > .05$). The PD_{50}, the Delta V at which a windshield has 50 percent chance of being penetrated, is:

	HPR	pre-HPR
rubber gasket	33.3	14.4
adhesive bonding	33.0	14.1

i.e., the windshield installation method is of little importance.

A more complex regression including the interaction term HPR x ADHESIVE did not show a significant effect for that term--i.e., adhesive bonding did not make a difference in pre-HPR nor in HPR cars.

These results are clear evidence that adhesive bonding did not make windshield penetration easier in crashes. If injuries did increase, it would have had to be through some other mechanism.

TABLE 6-2

WINDSHIELD PENETRATION BY WINDSHIELD INSTALLATION METHOD, DELTA V AND TYPE OF GLAZING, FRONT-SEAT OCCUPANTS IN FRONTAL CRASHES WITH WINDSHIELD CONTACT INJURIES (NCSS)

Delta V	Pre-HPR Windshields		HPR Windshields	
	Rubber Gaskets	Adhesive Bonding	Rubber Gaskets	Adhesive Bonding
	PERCENT OF OCCUPANTS WHO PENETRATED THE WINDSHIELD			
1-4	--	--	0	0
5-9	35	50	0	0
10-14	58	29	3	7
15-19	67	30	15	6
20-24	86	83	9	26
25-29	83	--	18	21
30-34	75	0*	54	25
35-39	0*	--	75	41
40+	0*	--	86	69
	SAMPLE SIZES FOR PRECEDING TABLE			
1-4	0	0	9	15
5-9	26	2	106	206
10-14	33	7	150	472
15-19	12	23	118	478
20-24	14	6	67	247
25-29	12	0	34	128
30-34	8	1	13	104
35-39	4	0	4	27
40+	1	0	7	29

*Windshields apparently broke before being contacted by occupants.

6.2 New York State data on head injuries

In Chapter 4, NCSS injury data were analyzed first because they identify the contact point as well as the type of injury. Here, however, the effects being studied are too small to expect statistically meaningful results if NCSS data are subdivided by contact point and injury type. New York State, which has a much larger sample and identifies the body region injured and the type of lesion (see Section 3.3) becomes the file of first choice.

Three separate analyses will be conducted with New York data on front-seat occupants in frontal crashes (and also with Texas data, later on):

- o effect of adhesive bonding in domestic cars with HPR windshields
- o adhesive bonding in pre-HPR domestic cars
- o effect of Standard 212 in Volkswagens

Thus, the first analysis is limited to 1966 and later model years. Moreover, in order to keep the data "balanced" between rubber gaskets and adhesive bonding, it is further limited to the following model years:

- o Models that first received adhesive bonding in 1967 - use only MY 1966-67

- o Models that first received adhesive bonding in 1968 - use only MY 1966-69

- o Models that first received adhesive bonding in 1969 - use only MY 1966-71

- o Models that first received adhesive in 1970 or 1971 - use all ±4 model years

The analysis of adhesive bonding in pre-HPR cars is limited to models which received adhesive bonding in 1965 and had rubber gaskets in earlier years (see Table 1-1). A strictly "balanced" study should only compare those cars between model year 1964 and 1965 (last year before versus first year after). But because of critical shortages of data, model years 1961-63 are also considered.

The analysis of Volkswagens is limited to MY 1966-73 (Standard 212's effective date ±4 years).

As in Sections 3.3 and 4.3, five types of head-face-neck injury will be considered in New York: "severe" bleeding, fractures, minor bleeding, concussions plus "internal" injuries, contusions plus complaints of pain.

6.2.1 Adhesive bonding in cars with HPR windshields

Table 6-3 shows that adhesive bonding did not increase the risk of any of the five types of head injuries in domestic cars with HPR windshields--in fact, the injury rate in cars with adhesive bonding is often lower than with rubber gaskets.

TABLE 6-3

HEAD* INJURY RATES BY WINDSHIELD INSTALLATION METHOD AND INJURY TYPE, DOMESTIC CARS WITH HPR WINDSHIELDS, FRONT-SEAT OCCUPANTS IN FRONTAL CRASHES (NEW YORK STATE, 1974)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Change for Adhesive Bonding (%)
		INJURIES WITH SEVERE BLEEDING		
Last MY w. rubber gaskets	90	3585	25.10	
First MY w. adhesive bonding	92	4226	21.77	13 reduction
Last 2 w. rubber gaskets	156	7103	21.96	
First 2 w. adhesive bonding	142	7559	18.79	14 reduction
Last 3 w. rubber gaskets	226	9755	23.17	
First 3 w. adhesive bonding	189	10,486	18.02	22 reduction
Last 4 w. rubber gaskets	243	10,504	23.13	
First 4 w. adhesive bonding	209	11,698	17.87	23 reduction
		FRACTURES		
Last MY w. rubber gaskets	13	3585	3.63	
First MY w. adhesive bonding	13	4226	3.08	15 reduction
Last 2 w. rubber gaskets	26	7103	3.66	
First 2 w. adhesive bonding	25	7559	3.31	10 reduction
Last 3 w. rubber gaskets	33	9755	3.38	
First 3 w. adhesive bonding	35	10,486	3.34	1 reduction
Last 4 w. rubber gaskets	34	10,504	3.24	
First 4 w. adhesive bonding	37	11,698	3.16	2 reduction
		INJURIES WITH MINOR BLEEDING		
Last MY w. rubber gaskets	368	3585	102.65	
First MY w. adhesive bonding	391	4226	92.52	10 reduction
Last 2 w. rubber gaskets	752	7103	105.87	
First 2 w. adhesive bonding	665	7559	87.97	17 reduction
Last 3 w. rubber gaskets	1027	9755	105.28	
First 3 w. adhesive bonding	925	10,486	88.21	16 reduction
Last 4 w. rubber gaskets	1109	10,504	105.58	
First 4 w. adhesive bonding	1030	11,698	88.05	17 reduction

TABLE 6-3 (Continued)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Change for Adhesive Bonding (%)
CONCUSSIONS AND "INTERNAL" HEAD INJURIES				
Last MY w. rubber gaskets	36	3585	10.04	
First MY w. adhesive bonding	37	4226	8.76	13 reduction
Last 2 w. rubber gaskets	70	7103	9.85	
First 2 w. adhesive bonding	81	7559	10.72	9 increase
Last 3 w. rubber gaskets	99	9755	10.15	
First 3 w. adhesive bonding	108	10,486	10.29	1 increase
Last 4 w. rubber gaskets	115	10,504	10.95	
First 4 w. adhesive bonding	127	11,698	10.86	1 reduction
CONTUSIONS AND COMPLAINTS OF PAIN				
Last MY w. rubber gaskets	276	3585	76.99	
First MY w. adhesive bonding	342	4226	80.93	5 increase
Last 2 w. rubber gaskets	580	7103	81.66	
First 2 w. adhesive bonding	639	7559	84.53	4 increase
Last 3 w. rubber gaskets	813	9755	83.34	
First 3 w. adhesive bonding	872	10,486	83.16	no change
Last 4 w. rubber gaskets	867	10,504	82.54	
First 4 w. adhesive bonding	983	11,698	84.05	2 increase

*Head, face or neck

Occupants of cars with adhesive bonding had fewer head injuries with severe bleeding than cars with rubber gaskets. The sequence of reductions for the ±1, ±2, ±3 and ±4 model year comparisons are 13, 14, 22 and 23 percent. The observed reductions are obviously not due to chance alone (Chi-square for the 4 year comparison is 7.70, $p < .05$) but they are also unlikely to be due to adhesive bonding. The most likely reason would appear to be the "delayed onset" of the full effects of HPR which was noted in Section 4.3.1, especially in Ford Motor Company cars.

Facial fractures are rarer than severe bleeding and as a result, the sequence of reductions of fractures--15, 10, 1 and 2 percent--has some fluctuation in the small-sample comparisons. But it appears to be converging on zero effect.

Nonminor lacerations and fractures are believed to be the two types of injury most commonly associated with windshield penetration (see Section 1.3). Thus, the New York findings that adhesive bonding did not increase these injuries is consistent with the NCSS results which showed it to have little or no effect on penetration velocities.

Adhesive bonding did not appear to increase the risk of injuries with minor bleeding. In fact, lower risk was associated with adhesive bonding: 10, 17, 16, 17 is the sequence of reductions. It is unlikely that the reductions are due to adhesive bonding, though. Similarly puzzling reductions were found for HPR windshields (Table 4-20). Vehicle age effects, redesign of passenger compartment geometry, and a change from plate glass to float glass in certain windshields offer a more likely explanation.

If a loose, flexible rubber gasket is of value as an energy-absorbing device or if its tearing away acts as a force limiter, then blunt impact trauma ought to increase with adhesive bonding. But Table 6-3 shows no significant increases in concussions (major blunt impact trauma) or contusions and complaints of pain (minor blunt impact trauma). The sequence of estimates for concussions--13 reduction, 9 increase, 1 increase, 1 reduction--converges to near zero after some small-sample fluctuations. The sequence for contusions and complaints of pain is based on much larger numbers of injuries and is less prone to random fluctuations. The estimates--5 increase, 4 increase, no change, 2 increase--could be indicative of a convergence to near zero or, alternatively, a modest negative effect with a vehicle age-related trend that gradually compensates for the effect. But other analyses of minor blunt impact trauma in New York (Tables 4-22, 6-4 and 6-5) do not show vehicle age trends. Thus, the more likely explanation is that the effect of adhesive bonding is near zero.

6.2.2 Adhesive bonding in cars with pre-HPR windshields

Fargo's analysis of ACIR data, which attributed a 43 percent increase in nonminor windshield contact injuries to adhesive bonding, is based on cars with pre-HPR windshields. Table 6-4 shows that the New York data for pre-HPR windshields seem more or less consistent with Fargo's results although, as was shown above, adhesive bonding was harmless for HPR windshields.

Nonminor lacerations (head injuries with severe bleeding) were approximately 20 percent more likely in cars with adhesive bonding. The actual sequence of estimates was 21 increase, 16 increase, 21 increase, 17 increase. The third of these four increases is statistically significant (Chi-square = 2.86, one-sided $p < .05$) but the other three are not (e.g.,

TABLE 6-4

HEAD* INJURY RATES BY WINDSHIELD INSTALLATION METHOD AND INJURY TYPE, DOMESTIC CARS WITH PRE-HPR WINDSHIELDS, FRONT-SEAT OCCUPANTS IN FRONTAL CRASHES (NEW YORK STATE, 1974)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Change for Adhesive Bonding (%)
		INJURIES WITH SEVERE BLEEDING		
1964 (last MY w. rubber gaskets)	71	2325	30.54	
1965 (first MY w. adhesive bonding)	159	4291	37.05	21 increase
1963-64	123	3850	31.95	
1965	159	4291	37.05	16 increase
1962-64	138	4518	30.54	
1965	159	4291	37.05	21 increase**
1961-64	150	4753	31.56	
1965	159	4291	37.05	17 increase
		FRACTURES		
1964 (last MY w. rubber gaskets)	13	2325	5.59	
1965 (first MY w. adhesive bonding)	15	4291	3.50	37 reduction
1963-64	20	3850	5.19	
1965	15	4291	3.50	33 reduction
1962-64	21	4518	4.65	
1965	15	4291	3.50	25 reduction
1961-64	21	4753	4.42	
1965	15	4291	3.50	21 reduction
		INJURIES WITH MINOR BLEEDING		
1964 (last MY w. rubber gaskets)	234	2325	100.65	
1965 (first MY w. adhesive bonding)	465	4291	108.37	8 increase
1963-64	410	3850	106.49	
1965	465	4291	108.37	2 increase
1962-64	491	4518	108.67	
1965	465	4291	108.37	No change
1961-64	522	4753	109.82	
1965	465	4291	108.37	1 reduction

TABLE 6-4 (Continued)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Change for Adhesive Bonding (%)
CONCUSSIONS AND "INTERNAL" HEAD INJURIES				
1964 (last MY w. rubber gaskets)	16	2325	6.88	
1965 (first MY w. adhesive bonding)	48	4291	11.19	63 increase**
1963-64	28	3850	7.27	
1965	48	4291	11.19	54 increase**
1962-64	34	4518	7.53	
1965	48	4291	11.19	49 increase**
1961-64	34	4753	7.15	
1965	48	4291	11.19	56 increase**
CONTUSIONS AND COMPLAINTS OF PAIN				
1964 (last MY w. rubber gaskets)	168	2325	72.26	
1965 (first MY w. adhesive bonding)	367	4291	85.53	18 increase**
1963-64	280	3850	72.73	
1965	367	4291	85.53	18 increase**
1962-64	322	4518	71.27	
1965	367	4291	85.53	20 increase**
1961-64	336	4753	70.69	
1965	367	4291	85.53	21 increase**

*Head, face and neck
**Statistically significant increase for adhesive bonding (one-sided $p < .05$)

for the ±4 year estimate, Chi-square = 2.06, one-sided $p > .05$). These levels of significance, by themselves, are not convincing evidence that adhesive bonding increased nonminor lacerations (and presumably reduced penetration velocities) in pre-HPR cars. Other data sources must also be taken into account (see Section 6.5).

Facial fractures did not increase; in fact, a sequence of reductions was observed: 37, 33, 25, 21. The estimates are based on small numbers of fractures and are, of course, not statistically significant. If these numbers have any real meaning at all, they could be construed as support for Patrick's hypothesis that when windshields separate from the frame, there is potential for significant injuries (viz., facial fractures) due to contact with the exposed windshield frame or the car's hood (see Section 2.2.2).

The sequence of estimated effects on injuries with minor bleeding (minor lacerations)--8 increase, 2 increase, no change, 1 reduction--is evidently converging on "little or no effect."

The New York data show significant increases in blunt impact trauma, both major and minor, consistent with Fargo's results. The sequence of estimates for concussions and "internal" head injuries--63 increase, 54 increase, 49 increase, 56 increase--is consistent and each increase is statistically significant (Chi-squares are 2.92, 3.36, 3.20, 4.08; one-sided $p < .05$ in each case). On the other hand, the results are based on small numbers of injuries and could have a lot of sampling error--e.g., the real effect might be considerably smaller.

The results for minor blunt impact trauma are even more clear-cut. The sequence of estimates for contusions and complaints of pain is 18 increase, 18 increase, 20 increase, 21 increase. Each increase is statistically significant (Chi-squares are 3.57, 4.55, 6.20 and 6.93.)

Although this is strong evidence that blunt impact trauma increased in those makes and models which received adhesive bonding in 1965, final judgment should be suspended until after the analysis of Texas data.

6.2.3 Effect of Standard 212 in Volkswagens

When Rodloff and Breitenbuerger studied the effect of windshield bonding on the velocity required to penetrate glazing in a drop test, they were comparing a "controlled pop-out attachment" to "very rigid clamping" (see Section 2.2.1). Perhaps the preceding analyses are irrelevant to their hypothesis since American cars, when they changed from rubber gaskets to adhesive bonding, only moved from "rigid" to "very rigid" clamping (see Section 5.1). But Volkswagens really did have virtually "pop-out" windshields before Standard 212 and fairly tight bonding afterwards. How did Standard 212 affect head injury risk in those cars, which had HPR windshields both before and after Standard 212's 1970 effective date?

Table 6-5 shows that nonminor lacerations were not increased by Standard 212. The sequence of estimates was 4 reduction, 1 increase, 4 reduction, 21 reduction. The first three numbers clearly suggest "little or no effect" for Standard 212. The anomalous fourth estimate, due to a much higher injury late in model year 1966, suggests that Volkswagens may still have had pre-HPR windshields in that year.

The results for facial fractures are hardly worth reporting because they are based on so few injuries (e.g., only 1 in MY 1969). They appear to be converging on "little or no change" although even that is not certain.

TABLE 6-5

HEAD* INJURY RATES IN VOLKSWAGENS BY STANDARD 212 COMPLIANCE AND INJURY TYPE, FRONT-SEAT OCCUPANTS IN FRONTAL CRASHES (NEW YORK STATE, 1974)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Change for Standard 212 (%)
INJURIES WITH SEVERE BLEEDING				
1969 (last yr. before Std. 212)	26	957	27.17	
1970 (first yr. after Std. 212)	22	842	26.13	4 reduction
1968-69	47	1641	28.64	
1970-71	54	1871	28.86	1 increase
1967-69	60	2155	27.84	
1970-72	71	2667	26.62	4 reduction
1966-69	87	2648	32.86	
1970-73	93	3590	25.91	21 reduction
FRACTURES				
1969 (last yr. before Std. 212)	1	957	1.04	
1970 (first yr. after Std. 212)	5	842	5.94	468 increase
1968-69	5	1641	3.05	
1970-71	11	1871	5.88	93 increase
1967-69	8	2155	3.71	
1970-72	15	2667	5.62	52 increase
1966-69	10	2648	3.78	
1970-73	15	3590	4.18	11 increase
INJURIES WITH MINOR BLEEDING				
1969 (last yr. before Std. 212)	154	957	160.92	
1970 (first yr. after Std. 212)	118	842	140.14	13 reduction
1968-69	254	1641	154.78	
1970-71	240	1871	128.27	17 reduction
1967-69	335	2155	155.45	
1970-72	343	2667	128.27	17 reduction
1966-69	419	2648	158.23	
1970-73	444	3590	123.68	22 reduction

TABLE 6-5 (Continued)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Change for Standard 212 (%)
CONCUSSIONS AND "INTERNAL" HEAD INJURIES				
1969 (last yr. before Std. 212)	16	957	16.72	
1970 (first yr. after Std. 212)	15	842	17.81	7 increase
1968-69	26	1641	15.84	
1970-71	24	1871	12.83	19 reduction
1967-69	35	2155	16.24	
1970-72	35	2667	13.12	19 reduction
1966-69	47	2648	17.25	
1970-73	50	3590	13.93	22 reduction
CONTUSIONS AND COMPLAINTS OF PAIN				
1969 (last yr. before Std. 212)	89	957	93.00	
1970 (first yr. after Std. 212)	94	842	111.64	20 increase
1968-69	165	1641	100.55	
1970-71	210	1871	112.24	12 increase
1967-69	225	2155	104.41	
1970-72	301	2667	112.86	8 increase
1966-69	267	2648	100.83	
1970-73	400	3590	111.42	11 increase

Injuries with minor bleeding certainly did not increase as a result of Standard 212. In fact, a sequence of reductions--13, 17, 17 and 22 percent--was observed. These unexplained reductions parallel the ones found in other tabulations of cars of similar age (Tables 4-20 and 6-3) and are probably unrelated to Standard 212.

The estimates on concussions--7 increase, 19 reduction, 19 reduction, 22 reduction--although based on relatively small numbers of injuries, evidently do not suggest that Standard 212 increased concussions. The concussion rate per 1000 occupants is higher in Volkswagens than in American cars (Table 6-3). That is probably due to factors unrelated to the windshield mounting technique; nevertheless it cannot be considered a "plus" for pop-out windshields.

Minor blunt impact trauma was reported more frequently in post-Standard 212 cars. The sequence of estimates for contusions and complaints of pain was 20 increase, 12 increase, 8 increase and 11 increase. It is likely that most if not all of the increase was unrelated to Standard 212 and due to the fact that only one injury is reported in New York. Since other, more serious injuries decreased (e.g., lacerations, as shown earlier in Table 6-5 and thoracic injuries, as a result of energy-absorbing steering assemblies), headaches and bruises would not be reported whereas, previously, a more serious injury would be reported and the minor one omitted.

6.3 NCSS data on windshield contact injuries

The NCSS sample is too small to be broken up into pre-HPR vs. post-HPR cars, lacerations vs. concussions, etc. Classifying the injuries by type of lesion made sense in Chapter 4, where effects on the order of 50-75 percent were anticipated for HPR: it doesn't take a large sample to detect an effect of that magnitude. Here, it would merely result in many tables of meaningless little numbers. Nevertheless, NCSS is unique in that it allows windshield-related injuries (windshield contacts, windshield ejections and secondary neck injuries--see Section 3.2) to be distinguished from other casualties. It is best to examine the aggregate effect of adhesive bonding on windshield-related injuries in domestic cars (HPR and pre-HPR, combined).

6.3.1 Nonminor injuries

Table 6-6 shows the probability that occupants are hospitalized (at least overnight--see Section 3.2) as a consequence of windshield-related injuries. The changes in this probability associated with adhesive bonding, as measured in the ±1, ±2, ±3, ±4 and ±5 model year comparisons, are 2 reduction, 58 increase, 35 increase, 9 increase, 4 increase. In other words, after some initial fluctuations due to the small sample sizes, the estimates appear to be converging on "little or no effect."

Table 6-7 measures the risk of nonminor injury differently, counting the actual number of AIS ≥ 2 windshield-related injuries per 1000 occupants. (There may be more than one such injury reported per occupant.) Here, the sequence of estimates is 30 reduction, 15 reduction, 9 reduction, 14 reduction and 13 reduction.

The modest increases shown in Table 6-6, together with the small reductions in Table 6-7, suggest that adhesive bonding had little effect on the risk of nonminor windshield-related injury. Since most of the cars on NCSS have HPR windshields, the findings confirm New York results showing little or no effect of adhesive bonding in cars with HPR glazing.

TABLE 6-6

PERSONS HOSPITALIZED BY WINDSHIELD-RELATED* INJURIES, BY WINDSHIELD INSTALLATION METHOD, DOMESTIC CARS (NCSS)

Model Years	n of Hospitalizations	N of Persons	Casualties per 1000 Persons	Change for Adhesive Bonding (%)
Last MY w. rubber gaskets	20	2666	7.50	
First MY w. adhesive bonding	24	3254	7.38	2 reduction
Last 2 w. rubber gaskets	30	5694	5.29	
First 2 w. adhesive bonding	54	6483	8.33	58 increase
Last 3 w. rubber gaskets	43	8274	5.20	
First 3 w. adhesive bonding	76	10,800	7.04	35 increase
Last 4 w. rubber gaskets	64	10,557	6.06	
First 4 w. adhesive bonding	99	15,033	6.59	9 increase
Last 5 w. rubber gaskets	77	12,558	6.13	
First 5 w. adhesive bonding	134	20,939	6.40	4 increase

*Injuries due to windshield contact, windshield ejection or secondary neck injury

TABLE 6-7

NONMINOR (AIS $\geq$ 2) WINDSHIELD-RELATED* INJURIES, BY WINDSHIELD INSTALLATION METHOD, DOMESTIC CARS (NCSS)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Change for Adhesive Bonding (%)
Last MY w. rubber gaskets	27	2672	10.10	
First MY w. adhesive bonding	23	3255	7.07	30 reduction
Last 2 w. rubber gaskets	54	5705	9.47	
First 2 w. adhesive bonding	52	6489	8.01	15 reduction
Last 3 w. rubber gaskets	68	8286	8.21	
First 3 w. adhesive bonding	81	10,808	7.49	9 reduction
Last 4 w. rubber gaskets	85	10,572	8.04	
First 4 w. adhesive bonding	104	15,044	6.91	14 reduction
Last 5 w. rubber gaskets	95	12,633	7.52	
First 5 w. adhesive bonding	137	20,954	6.54	13 reduction

*Injuries due to windshield contact, windshield ejection or secondary neck injury

6.3.2 Minor injuries

Just as in the preceding section, there are two ways to measure the effect of adhesive bonding on minor windshield-related injuries. Table 6-8 examines the proportions of occupants who were transported to emergency rooms for treatment of windshield-related injuries. The sequence of estimates is 17 increase, 34 increase, 19 increase, 4 reduction, 5 reduction. Table 6-9 counts the actual number of minor windshield-related injuries per 1000 occupants. The sequence of estimates is 62 increase, 90 increase, 40 increase, 3 increase, 2 increase. Both sequences show a large amount of fluctuation at the start. This is because many of the injuries come from the 25 percent sampling stratum (or, in Table 6-9, even the 10 percent stratum) of NCSS. Thus, the numbers of injuries in the tables are much larger than the actual numbers of cases they are based on--greatly increasing the sampling error. Both sequences, however, converge on "little or no effect."

6.4 Texas data on overall injury rates

Texas police do not classify the body region or type of injury. They use the severity codes A, B and C (see Section 3.4). But the very large sample, especially of older cars, that can be derived from 3 years of Texas data (1972-74) offers a hope of detecting small changes in the injury rates of drivers in frontal crashes.

In section 4.3, it was shown that the HPR windshield significantly reduced (by 12 percent) the likelihood of level A injuries and had little or no effect on level B or C injuries. In other words, nonminor lacerations involving penetration of the windshield are typically classified level A. If, as suggested by Fargo and Rodloff, approximately half of the penetration-reducing benefit of HPR is defeated by tightly bonding the

TABLE 6-8

PERSONS TRANSPORTED TO EMERGENCY ROOMS FOR TREATMENT OF WINDSHIELD-RELATED*
INJURIES, BY WINDSHIELD INSTALLATION METHOD, DOMESTIC CARS (NCSS)

Model Years	n of Persons Transported	N of Persons Involved	Casualties per 1000 Persons	Change for Adhesive Bonding (%)
Last MY w. rubber gaskets	89	2672	33.31	
First MY w. adhesive bonding	127	3255	39.02	17 increase
Last 2 w. rubber gaskets	172	5705	30.15	
First 2 w. adhesive bonding	263	6489	40.53	34 increase
Last 3 w. rubber gaskets	256	8286	30.90	
First 3 w. adhesive bonding	398	10,808	36.82	19 increase
Last 4 w. rubber gaskets	376	10,572	35.57	
First 4 w. adhesive bonding	514	15,044	34.16	4 reduction
Last 5 w. rubber gaskets	457	12,633	36.18	
First 5 w. adhesive bonding	722	20,954	34.46	5 reduction

*Injuries due to windshield contact, windshield ejection or secondary neck injury

TABLE 6-9

MINOR WINDSHIELD-RELATED INJURIES, BY WINDSHIELD INSTALLATION METHOD, DOMESTIC CARS (NCSS)

Model Years	n of Injuries	N of Persons	Injuries per 1000 Persons	Change for Adhesive Bonding (%)
Last MY w. rubber gaskets	110	2672	41.17	
First MY w. adhesive bonding	217	3255	66.67	62 increase
Last 2 w. rubber gaskets	208	5705	36.46	
First 2 w. adhesive bonding	449	6489	69.19	90 increase
Last 3 w. rubber gaskets	366	8286	44.17	
First 3 w. adhesive bonding	667	10,808	61.71	40 increase
Last 4 w. rubber gaskets	571	10,572	54.01	
First 4 w. adhesive bonding	833	15,044	55.37	3 increase
Last 5 w. rubber gaskets	701	12,633	55.49	
First 5 w. adhesive bonding	1187	20,954	56.65	2 increase

windshield, something on the order of a 6 percent increase in level A injuries should be anticipated for the tighter installation methods. If, moreover, tighter bonding increases blunt impact trauma, similar increases could be expected in any of the 3 severity levels.

6.4.1 Adhesive bonding in cars with HPR windshields

Table 6-10, which is based on balanced samples of domestic cars with HPR windshields (see Section 6.2), does not suggest that adhesive bonding increased the risk of level A injuries for drivers in frontal crashes. In fact, the injury rate was reduced by 2, 5, 4 and 7 percent in the ±1, ±2, ±3 and ±4 year comparisons. That sequence of estimates suggests a vehicle age-related trend of about 2 percent per year and zero net effect for adhesive bonding.

Table 6-10 also provides a sequence of estimates for the rate of level A or B injuries: 4 increase, 3 reduction, 6 reduction, 7 reduction. The first estimate, which is based on the smallest sample, seems a bit out of line with the others. The last 3 estimates appear to suggest an age-related trend of about 2-3 percent per year and a net effect for adhesive bonding that is close to zero. The results for all types of injuries--A, B or C--are nearly identical.

The Texas data are further confirmation that adhesive bonding had little or no effect on the injuries of nonejected occupants of cars with HPR windshields.

6.4.2 Adhesive bonding in cars with pre-HPR windshields

Table 6-11 suggests that adhesive bonding did not increase the risk of level A injuries in cars with pre-HPR windshields. The observed injury rate was 2, 3, 4 and 6 percent lower in the cars with adhesive

TABLE 6-10

DRIVER INJURY RATES IN FRONTAL CRASHES, BY WINDSHIELD INSTALLATION METHOD, DOMESTIC CARS WITH HPR WINDSHIELDS (TEXAS, 1972-74)

Model Years	n of Injuries	N of Drivers	Injuries per 1000 Drivers	Change for Adhesive Bonding (%)
		LEVEL "A" OR FATAL INJURIES		
Last MY w. rubber gaskets	187	7687	24.33	
First MY w. adhesive bonding	209	8777	23.81	2 reduction
Last 2 w. rubber gaskets	455	17,934	25.37	
First 2 w. adhesive bonding	365	15,223	23.98	5 reduction
Last 3 w. rubber gaskets	686	27,474	24.97	
First 3 w. adhesive bonding	466	19,424	23.99	4 reduction
Last 4 w. rubber gaskets	752	29,355	25.62	
First 4 w. adhesive bonding	472	19,859	23.77	7 reduction
		LEVEL "A", "B" OR FATAL INJURIES		
Last MY w. rubber gaskets	639	7687	83.13	
First MY w. adhesive bonding	756	8777	86.13	4 increase
Last 2 w. rubber gaskets	1566	17,934	87.32	
First 2 w. adhesive bonding	1293	15,223	84.94	3 reduction
Last 3 w. rubber gaskets	2429	27,474	88.41	
First 3 w. adhesive bonding	1622	19,424	83.50	6 reduction
Last 4 w. rubber gaskets	2621	29,355	89.29	
First 4 w. adhesive bonding	1655	19,859	83.34	7 reduction
		ANY TYPE OF INJURY		
Last MY w. rubber gaskets	906	7687	117.86	
First MY w. adhesive bonding	1076	8777	122.59	4 increase
Last 2 w. rubber gaskets	2193	17,934	122.28	
First 2 w. adhesive bonding	1851	15,223	121.59	1 reduction
Last 3 w. rubber gaskets	3408	27,474	124.04	
First 3 w. adhesive bonding	2356	19,424	121.29	2 reduction
Last 4 w. rubber gaskets	3683	29,355	125.46	
First 4 w. adhesive bonding	2403	19,859	121.00	4 reduction

bonding in the MY 1964 vs. 65, 63-64 vs. 65, 62-64 vs. 65 and 61-64 vs. 65 comparisons, respectively. The sequence suggests an age-related trend of about 2 percent per year and a net effect for adhesive bonding which is close to zero. The results do not support the findings from New York (Section 6.2.2) or ACIR (Fargo--Section 2.3.1) but they are not entirely incompatible, statistically. As mentioned above, Fargo's results are comparable to a 6 percent increase in level A injuries. Given the sample sizes upon which Table 6-11 is based, the observed result of zero effect has confidence bounds of approximately ± 8 percent and encompasses the possibility of a 6 percent increase.

But Table 6-11 suggests more strongly that adhesive bonding did not increase level B and C injuries. Level A or B injury rates decreased by 7, 9, 10 and 10 percent in the four comparisons. That suggests the presence of a vehicle age-related trend of about 2 percent per year and a 5 percent reduction if the trend is removed. The reduction is probably unrelated to the windshield installation method. The results for injuries of all types (A, B or C) are virtually the same. Unlike the case of level A injuries, there are large enough samples of B and C injuries to allow a statistically confident conclusion that such injuries did not increase. Thus, the results are incompatible with New York and ACIR findings unless it is possible to identify a factor unrelated to windshields (e.g., redesign of the instrument panel) which eliminated so many torso, arm or leg injuries as to obscure the negative effect of adhesive bonding on head injuries. It is doubtful that any such factor exists.

TABLE 6-11

DRIVER INJURY RATES IN FRONTAL CRASHES, BY WINDSHIELD INSTALLATION METHOD, DOMESTIC CARS WITH PRE-HPR WINDSHIELDS (TEXAS, 1972-74)

Model Years	n of Injuries	N of Drivers	Injuries per 1000 Drivers	Change for Adhesive Bonding (%)
		LEVEL "A" OR FATAL INJURIES		
1964 (last MY w. rubber gaskets)	517	16,132	32.05	
1965 (1st MY w. adhesive bonding)	624	19,918	31.33	2 reduction
1963-64	1048	32,489	32.26	
1965	624	19,918	31.33	3 reduction
1962-64	1306	39,935	32.70	
1965	624	19,918	31.22	4 reduction
1961-64	1456	43,651	33.36	
1965	624	19,918	31.33	6 reduction
		LEVEL "A", "B" OR FATAL INJURIES		
1964 (last MY w. rubber gaskets)	1661	16,132	102.96	
1965 (1st MY w. adhesive bonding)	1899	19,918	95.34	7 reduction
1963-64	3394	32,489	104.47	
1965	1899	19,918	95.34	9 reduction
1962-64	4213	39,935	105.50	
1965	1899	19,918	95.34	10 reduction
1961-64	4623	43,651	105.91	
1965	1899	19,918	95.34	10 reduction
		ANY TYPE OF INJURY		
1964 (last MY w. rubber gaskets)	2231	16,132	138.30	
1965 (1st MY w. adhesive bonding)	2604	19,918	130.74	5 reduction
1963-64	4582	32,489	141.03	
1965	2604	19,918	130.74	7 reduction
1962-64	5631	39,935	141.00	
1965	2604	19,918	130.74	7 reduction
1961-64	6164	43,651	141.21	
1965	2604	19,918	130.74	7 reduction

6.4.3 Regression analysis for domestic cars

The primary advantage of Texas data for this study is its large sample size. Much of the advantage was lost in the preceding analyses when the cars were subdivided into pre- and post-HPR and many make/model/model year combinations had to be discarded to achieve "balanced" samples. Regression analyses make it possible to use more of the available data, viz., all cars built within ± 4 years of the transition to adhesive bonding (see Sections 3.9.1 and 4.4.2).

When the dependent variable is the percentage of drivers in frontal crashes who have level A or fatal injuries, the equation that best fits the observed, weighted data (R^2 = .89, df = 16) is:

$$
\begin{aligned}
\text{Rate (\%)} = {} & 2.246 + 0.119\ \text{ADHESIVE} \\
& + 0.075\ \text{AGE} + 0.002\ \text{AGE}^2 \\
& - 0.447\ \text{STD203} - 0.366\ \text{HPR} \\
& + 0.472\ \text{CY72} + 0.215\ \text{CY73}
\end{aligned}
$$

When the current average values 7, 1, 1, .32 and .35 are substituted for AGE, STD203, HPR, CY72 and CY73, respectively, the predicted injury rates are

- o 2.28 percent with rubber gaskets
- o 2.40 percent with adhesive bonding

This is a 5 percent increase for adhesive bonding, which is, however, not statistically significant since the F-value for the ADHESIVE term is only 0.55. In this case, the regression did not add any precision to the results.

When the dependent variable is the rate of A, B or fatal injuries, the equation that best fits the data ($R^2 = .92$, df = 17) is

$$\begin{aligned} RATE = {} & 7.60 + 0.10\ ADHESIVE \\ & +0.21\ AGE + 0.008\ AGE^2 \\ & -1.53\ STD203 \\ & +0.11\ CY72 + 0.06\ CY73 \end{aligned}$$

When current average values are substituted for the other independent variables, the predicted injury rates are

o 7.99 percent with rubber gaskets

o 8.09 percent with adhesive bonding

This is a 1 percent increase for adhesive bonding which, of course, is not statistically significant (F = 0.08).

When the dependent variable is the overall injury rate (A, B, C or fatal), the regression equation (R^2 = .94, df = 17) is

$$\begin{aligned} RATE = {} & 10.29 + 0.24\ ADHESIVE \\ & +0.34\ AGE + 0.005\ AGE^2 \\ & -0.99\ STD203 \\ & -0.06\ CY\ 72 - 0.16\ CY73 \end{aligned}$$

The predicted injury rates are

- o 11.85 percent with rubber gaskets
- o 12.09 percent with adhesive bonding

This 2 percent increase for adhesive bonding is not statistically significant (F = 0.58).

In short, the regressions shed little light on the effects of adhesive bonding.

6.4.4 Effect of Standard 212 in Volkswagens

Table 6-12 suggests that Standard 212 did not have any appreciable effect on the injuries of drivers of Volkswagens which were involved in frontal impacts in Texas. The table is limited to model years 1968-72: prior to 1968, VW's were not equipped with energy-absorbing steering columns and had considerably higher injury rates--because of the columns, not Standard 212.

TABLE 6-12

DRIVER INJURY RATES IN FRONTAL CRASHES, BY STANDARD 212 COMPLIANCE, VOLKSWAGENS WITH HPR WINDSHIELDS AND ENERGY-ABSORBING STEERING COLUMNS (TEXAS, 1972-74)

Model Years	n of Injuries	N of Drivers	Injuries per 1000 Drivers	Change for Std. 212 (%)
		LEVEL "A" OR FATAL INJURIES		
1969 (last yr. before Std. 212)	108	2929	36.87	
1970 (first yr. after Std. 212)	112	3064	36.55	1 reduction
1968-69	207	5656	36.59	
1970-71	232	6467	35.87	2 reduction
		LEVEL "A", "B" OR FATAL INJURIES		
1969	432	2929	147.49	
1970	451	3064	147.19	No change
1968-69	830	5656	146.75	
1970-71	884	6467	136.69	7 reduction
		ANY TYPE OF INJURY		
1969	556	2929	189.82	
1970	581	3064	189.62	No change
1968-69	1070	5656	189.18	
1970-71	1147	6467	177.36	6 reduction

Level A injury rates were 1 percent lower in the post-Standard 212 cars in the ±1 year comparison and 2 percent lower in the ±2 year comparison, suggesting little or no effect for Standard 212.

Level A or B injuries were unchanged in the ±1 year comparison and dropped by 7 percent in the ±2 year comparison. Since the vehicle age-related trend in Texas is typically 2-3 percent per year for level B injuries (see Tables 6-10 and 6-11), it would appear that the net effect of Standard 212 is close to zero. A similar conclusion can be drawn for the overall (A, B or C) injury rates.

6.5 Summary

The NCSS data on penetration velocities, the New York data on head injuries, the windshield-related injury rates in NCSS and the overall injury rates in Texas provide overwhelming evidence that adhesive bonding did not increase the injury risk of occupants who were not ejected in a crash, provided that the car was equipped with an HPR windshield. Even in Volkswagens, where Standard 212 brought about a more dramatic tightening of the windshield bond than took place in American cars, crash injuries did not increase.

Thus, the accident data strongly support Patrick's (Section 2.2.2) and Trosien's (Section 2.2.3) findings, based on sled tests with dummies and cadavers, that the windshield installation method had little effect on penetration velocities or blunt impact forces. It must be concluded that the sled tests more or less realistically simulated windshield performance in real crashes. It should also be concluded that the HPR windshield is not a good medium for transmitting occupant impact forces to the periphery; as a result, the potential benefits of looser windshield mounting are limited.

The accident data do not support Rodloff and Breitenbuerger's contention that rigid mounting defeats much of the benefit of HPR glazing. Their conclusion was based on drop tests using 20 x 30 inch panels of glazing and a 22 pound headform. It must be concluded that these tests did not accurately simulate the head/windshield/frame interaction that occurs in highway accidents. The most likely explanation is that the small size of the glazing panel made it easier to transmit forces to the periphery. It is also possible that the layout of a drop test and the impact angles facilitated the pullout of the glazing from the frame. As for Fargo's (Section 2.3.1) claims that adhesive bonding was harmful in HPR windshields, they are based on anecdotal information and secondary inferences; his actual statistical analysis deals with the effect of adhesive bonding in pre-HPR cars.

In cars with pre-HPR windshields, the analyses of New York State data give fairly strong support to Fargo's conclusions that adhesive bonding did increase head injuries--both lacerations and blunt impact trauma. On the other side of the coin, however, there are the analyses of NCSS data on penetration velocities and Texas data on overall injury rates, both based on less-than-adequate samples, which did not show a negative effect for adhesive bonding. Also, there is a possibility that Fargo's ACIR data were biased toward higher injury rates in 1965, the model year for his adhesively-bonded sample (see Section 2.3.2). Above all, there is engineering intuition that a windshield which is penetrated so easily is unlikely to do a good job of transmitting forces to its periphery. At this time, the case for either side of the argument seems about equally strong. It is still unknown whether or not adhesive bonding increased injury risk in pre-HPR windshields.

But it is also a question that nobody should really care about any more. The pre-HPR windshield has joined the three-lane highway, the wooden railroad coach and the hydrogen-filled blimp on the scrapheap of transportation history. What is important is that, in the HPR windshield, adhesive bonding and Standard 212 have not increased injury risk within the vehicle and have significantly reduced the risk of ejection through the windshield portal.

CHAPTER 7

COSTS AND BENEFITS

One of the goals of the evaluation is to estimate the actual benefits and actual costs of changes in windshield glazing and bonding in a manner that allows a meaningful comparison of benefits and costs.

The benefits of HPR windshields are the number of injuries (facial lacerations and fractures) that will be prevented annually when all cars on the road have HPR glass--relative to a baseline case where all car on the road have pre-HPR windshields. Similarly, the cost of HPR glazing is the average fleetwide difference between the costs of an HPR windshield and a pre-HPR windshield. The cost includes the increase in the initial purchase price of a vehicle and the incremental fuel consumption due to the weight of thicker interlayer.

Two changes in windshield installation methods are analyzed: the changeover from rubber gaskets to adhesive bonding in American cars and the clipping of the rubber gasket to the frame of Volkswagens. The benefits are the numbers of lives and serious injuries saved as a consequence of fewer ejections. Benefits are calculated under the assumption that all cars already have the HPR windshield--i.e., that there are no disbenefits in terms of occupants who are not ejected sustaining more severe injuries (see Chapter 6). Costs, as before, represent the difference between the earlier and later installation method.

All costs are expressed in 1982 dollars.

7.1 Costs

7.1.1 HPR windshields

The incremental cost of the HPR windshield is low in comparison to other major safety standards. While safety devices such as head restraints or side door beams added significant new hardware to cars, HPR is primarily a technological advance--finding a way to do more with basically the same material (the laminated windshield). The most tangible cost increment is the increase in the thickness of the interlayer from 0.015 inches in pre-HPR laminated windshields to 0.030 inches in HPR. The other changes--adapting polyvinyl butyral to adhere less closely to glass and controlling the moisture content of the plastic during the lamination process--had little long-term cost.

A 1982 study performed under contract to NHTSA estimated that HPR glazing added $4.45 to the purchase price of a car and increased the weight by 1.05 pounds [12]. The "purchase price increase" is calculated from the value of materials, labor, tooling, assembly, overhead, manufacturer's and dealer's markups and taxes.

The General Accounting Office's report on the "Effectiveness, Benefits and Costs of Federal Safety Standards for Protection of Passenger Car Occupants" estimated that HPR (Standard 205) raised the purchase price of a car by $3, in 1974 dollars [8]. The estimate is based on an average of quotations supplied by the manufacturers. Based on the escalation in the

Consumer Price Index for new cars between 1974 and 1982, it is equivalent to $5.45, in 1982 dollars, which is reasonably close to the NHTSA contractor's estimate.

The 1.05 pound weight increase mentioned above should result in the consumption of 1.05 additional gallons of fuel over the life of a car [20], p. 134. The discounted value of the fuel, at 1982 prices, is $1.05.

HPR glazing is unlikely to have much effect on lifetime repair and maintenance costs. Its main effect is to change spider web damage with windshield penetration to similar damage without penetration--in either event the windshield would have to be replaced after a collision.

Thus, the total cost of HPR glazing is $5.50 per car, which is the sum of the purchase price increase ($4.45) and the fuel penalty ($1.05). Based on sales of 10 million cars per year in the United States, the total annual cost of HPR windshields is $55 million.

7.1.2 Windshield installation methods

Adhesive bonding resembles HPR windshields in that it is primarily a technical advance--the synthesis of resiliant sealing materials--than an addition of hardware to the car. On the contrary, the new bonding materials allowed the elimination of rubber gaskets in return for an inexpensive sealent and a minor increase in labor costs.

A 1980 study performed by a NHTSA contractor compared rubber gaskets to adhesive bonding in one passenger car (Plymouth Barracuda) and three light trucks [30]. On the Barracuda, the rubber gasket used in 1969 weighed 4.63 pounds and contributed $15.24 (in 1979 dollars) to the purchase price. (Note that the "consumer cost" numbers for windshield mounting throughout [30] inadvertently double-counted the "wholesale cost." The correct figures are contained in the "dealer markup" columns of page H-2, which is in fact wholesale cost plus dealer markup--i.e., consumer cost.) The materials and installation for butyl tape bonding in the 1970 Barracuda weighed 0.65 pounds and cost $5.91. Thus, adhesive bonding resulted in a net savings of 3.98 pounds and $9.33 (in 1979 dollars). The savings for the light trucks were slightly larger, because they have larger windshields.

Based on the escalation in the Consumer Price Index for new cars, the savings of $9.33 in 1979 dollars is equivalent to $11.50 in 1982 dollars. As explained above, the 3.98 pound weight saving will reduce the discounted value of the car's lifetime fuel consumption by $3.98.

Thus, the total saving for adhesive bonding is $15.48 per car, which is the sum of the purchase price reduction ($11.50) and the fuel credit ($3.98). Based on domestic car sales of 7.5 million per year, the total annual saving for adhesive bonding is $116 million. These estimates should be considered approximate rather than precise, as they are based on a single make/model of passenger car, supported by evidence from three types of light trucks.

The General Accounting Office's cost analysis, which was based on manufacturers' quotes, merely states that Standard 212 cost less than $1 per car [8]. It is not clear whether that implies a cost between zero and $1 or includes the possibility of a net savings.

The cost of Standard 212 is unknown for Volkswagens, where it led to the insertion of continuous clips between the rubber gasket and the pinchweld flange which frames it. The clips, however, appear to be much smaller and lighter than the gasket itself, so it is unlikely that they cost more than a few dollars per car.

7.2 The number of windshield-related injuries and the benefits of HPR glazing

Section 4.6 provided "best" estimates of the effectiveness of HPR glazing in preventing certain types of windshield contact injuries. They were:

- o 74 percent reduction of nonminor lacerations
- o 72 percent reduction of nonminor injuries to the eyes, nose or mouth
- o 56 percent reduction of facial fractures

- 25 percent reduction of minor lacerations

- little or no effect on concussions, minor blunt impact trauma or associated whiplash.

7.2.1 Number of injuries per year if HPR had not been implemented

In order to compute the benefits of HPR, it is necessary to estimate the numbers of injuries of each type that would have occurred in a recent year such as 1981 or 1982 if HPR glazing had not been implemented. This number is multiplied by the effectiveness to obtain the injuries saved by HPR.

In 1981-82, the average annual number of injured passenger car occupants, by overall AIS level, was:

		OCCUPANTS
Survivors with overall AIS	1	2,105,000
	2	264,000
	3	67,000
	4	9,000
	5	4,000
Fatalities		25,000

(The numbers of survivors are based on 1982 National Accident Sampling System data; fatalities are the average of 1981 and 1982 FARS.)

Each injured person, however, may have more than one injury and the injuries may be of different severity levels. In NCSS, the average number of injuries per injured occupant is shown in Table 7-1. These averages are multiplied by the preceding numbers of injured occupants to estimate how many individual injuries occur in a year:

	INJURIES
AIS 1	6,054,000
2	373,000
3	113,000
4	31,000
5	28,000
6	12,000

These injuries could involve any contact point, body region, lesion, etc. In order to determine the number of windshield-related injuries of a specific type, it is necessary to multiply the above figures by the proportion of injuries which involve a specific contact point (the windshield), body region, lesion, etc. The proportions are based on NCSS injuries with known contact points.

All calculations are carried out in Table 7-2. For example, "nonminor lacerations due to windshield contact," the type of injury that HPR was most effective in reducing, have AIS ranging from 2 to 4. There are a total of 517,000 individual injuries per year with AIS 2, 3 or 4. Out of 412 injuries with known contact points in pre-HPR cars on NCSS, 42 were nonminor lacerations due to windshield contact, which is 10.194 percent.

TABLE 7-1

AVERAGE NUMBER OF INJURIES PER INJURED OCCUPANT,
BY SEVERITY LEVEL (NCSS)

	Occupant's Overall AIS	Average number of injuries at AIS: 1	2	3	4	5	6
Survived	1	2.55	--	--	--	--	--
Survived	2	2.04	1.18	--	--	--	--
Survived	3	1.75	0.63	1.26	--	--	--
Survived	4	1.33	0.65	0.82	1.12	--	--
Survived	5	0.97	0.46	0.79	0.56	1.06	--
	Fatal	0.58	0.42	0.75	0.76	0.95	0.49

Thus, there would be 53,000 (10.194% of 517,000) nonminor lacerations due to windshield contact annually, if HPR had not been implemented. Similarly, there would be 26,000 nonminor injuries to the eyes, nose of mouth and 14,000 nonminor facial fractures. The three types are not mutually exclusive: in fact all of the eye-nose-mouth injuries in NCSS were either lacerations (including avulsions) or fractures. As a result, there are a total of 67,000 injuries per year in the three categories--the sum of the lacerations and the fractures.

The same procedure, using AIS 1 rather than AIS 2-4 injuries, permits an estimate of 569,000 minor lacerations per year if HPR had not been implemented.

In Chapter 4, HPR was found to have little or no effect on blunt impact trauma. In other words, the proportion of injuries which are, say, windshield-contact concussions should be about the same for pre-HPR and HPR cars. For these injury types, it is permissible to determine those proportions using NCSS data on cars of all ages rather than limiting oneself to the much smaller sample of pre-HPR cars. Table 7-2 indicates estimates of 21,000 windshield-contact concussions per year; 362,000 minor head injuries such as contusions or headaches due to blunt impact trauma; 74,000 persons who contacted the windshield with their head and also sustained minor whiplash in the neck; and 1,600 persons whose head hit the windshield and who had AIS $\geq$ 2 noncontact neck injury.

TABLE 7-2

NUMBER OF WINDSHIELD-RELATED INJURIES PER YEAR, IF HPR GLAZING HAD NOT BEEN IMPLEMENTED, BY INJURY TYPE

Windshield-Related Injury Type and AIS Level	Total No. of Injuries of All Types at those AIS Levels	NCSS Nos. of Injuries with Known Contact Points at these AIS Levels		Percent of Injuries that are of this Type	Annual No. of Injuries of this Type
		Of this Type	Of any Type		
	(T)	(i)	(n)	(r=i/n)	(N=rT)
Lacerations AIS 2-4	517,000	42*	412*	10.194	53,000
Eye-nose-mouth AIS 2-4	517,000	21*	412*	5.097	26,000
Fractures AIS 2-4	517,000	11*	412*	2.670	14,000
Total of above 3 types	517,000	53*	412*	12.864	67,000
Lacerations AIS 1	6,054,000	190*	2021*	9.401	569,000
Concussions, etc. AIS 2-6	557,000	251**	6587**	3.811	21,000
Blunt impact trauma AIS 1	6,054,000	3032**	42058**	7.209	362,000
Assoc. whiplash AIS 1	6,054,000	624**	42058**	1.229	74,000
Assoc. neck injury AIS 2-6	557,000	19**	6587**	0.288	1,600

* In cars with pre-HPR windshields
** In cars of all ages

In other words, prior to HPR, injuries associated with windshield penetration, such as lacerations and fractures, accounted for the overwhelming majority of nonminor windshield-related injuries (67,000 out of 89,600). Lacerations also accounted for the majority of minor injuries (569,000 out of 1,005,000).

7.2.2 Benefits of HPR

The benefits of HPR are calculated by multiplying the annual number of injuries (the last column of Table 7-2) by the effectiveness estimate, from Section 4.6, for injuries of that type. The results are shown in Table 7-3. For example, HPR glazing eliminates 74 percent of the 53,000 nonminor lacerations, which is a savings of 39,000 injuries per year. It saves 19,000 nonminor injuries of the eyes, nose or mouth and 8,000 fractures (AIS 2-4). Since all of the eye, nose or mouth injuries were lacerations (including avulsions) or fractures, the overall savings of nonminor injuries is 47,000, the sum of the estimates for the lacerations and the fractures. HPR windshields also eliminate an estimated 142,000 minor lacerations annually.

HPR has succeeded in eliminating so many lacerations and fractures that close to half of the nonminor windshield contact injuries that still remain are now concussions.

7.2.3 Confidence bounds

Confidence bounds (one-sided $\alpha = .05$) were calculated, first for the number of injuries without HPR and then for the benefit. All of them are shown in Table 7-3.

In Table 7-2, the formula for the annual number, N, of windshield-related injuries of a particular type

$$N = r\,T = i/n\;T$$

where T = total number of injuries of any type at those AIS levels

i = number of NCSS injuries of that type, in pre-HPR cars

n = number of NCSS injuries of any type at those AIS levels, known contact points, pre-HPR cars

r = i/n

T is based on much larger samples than r and may be treated, for practical purposes as a constant, not a random variable. Thus, the formula for N is a binominal multiplied by a constant. When i is greater than 30, it is appropriate to use the normal approximation, with confidence bounds:

$$N = \left(r \pm 1.645 \sqrt{\frac{r\,(1 - r)}{n}}\right) T$$

This formula yielded the confidence bounds for nonminor lacerations and "total of the above 3 types." It was also used for minor lacerations, except that there n was divided by 4 to take into account that NCSS cases

TABLE 7-3

ANNUAL BENEFITS OF HPR WINDSHIELDS

Type of Windshield-Contact Injury	Number of Injuries per Year, without HPR		Effectiveness of HPR (%)	Injuries Saved by HPR	
	Best Estimate	Confidence Bounds*		Best Estimate	Confidence Bounds*
Laceration AIS 2-4	53,000	40,000-66,000	74	39,000	25,000-53,000
Eye-nose-mouth AIS 2-4	26,000	17,000-37,000	72	19,000	9,700-29,000
Fracture AIS 2-4	14,000	7,700-21,400	56	8,000	1,000-18,000
Any of above 3 types	67,000	53,000-81,000		47,000	31,000-62,000
Laceration AIS 1	569,000	439,000-699,000	25	142,000	22,000-315,000

* One-sided alpha =.05

were weighted and all counts were inflated by a factor of approximately 4 (whereas all NCSS statistics on nonminor injuries in this report are based on the 100 percent sampling stratum, only).

When i is less than 30 and n is large, it is more satisfactory to assume that i has the Poisson distribution and to treat n as a constant. Thus, the confidence bounds are the Poisson bounds for i, multiplied by T/n. (See Chart I of [47] for .05 and .95 Poisson bounds.) This approach was used for eye-nose-mouth injuries and fractures.

In Table 7-3, benefits, B, for nonminor lacerations, eye-nose-mouth injuries and fractures are calculated directly from the formula

$$B = NE = \frac{i}{n} T \left(1 - \frac{i_2 / n_2}{i_1 / n_1} \right)$$

where N, i, n, T are as before

E = effectiveness

i_1 = number of injuries of that type, last 5 MY before HPR, NCSS

n_1 = number of persons, last 5 MY before HPR, NCSS

i_2 = number of injuries of that type, first 5 MY with HPR, NCSS

n_2 = number of persons, first 5 MY with HPR, NCSS.

The quantities i_1, n_1, i_2 and n_2 may be read directly from the $^+5$ year comparisons in Tables 4-1, 4-2 and 4-3 for nonminor lacerations, eye-nose-mouth injuries and fractures, respectively. (In Section 4.6, the NCSS $^+5$ year comparison was selected as the best effectiveness estimate for each of these injury types.) Of course, n, T, n_1 and n_2 can be treated as constants rather than random variables. So can i_2; even though it is not much larger than i_1, n_2 is so much larger than n_1 that i_2/n_2 will have little variance relative to i_1/n_1. That leaves i and i_1. These two variables have a correlation coefficient close to 1, since i_1 includes all injuries from model years 1961-66 in domestic cars and i merely adds to these MY 1960 domestic cars and MY 1960-66 foreign cars (of which there are very few in NCSS). The more correlated i and i_1 are, the higher the variance of B--so it is appropriate to make the worst-case assumption that the correlation coefficient is 1. In other words, i and i_1 are treated as Poisson variables and their lower bounds are simultaneously entered in the equation to obtain a lower bound for B--do likewise, for an upper bound.

Since all of the AIS 2-4 injuries eliminated by HPR in NCSS were either lacerations (including avulsions) or fractures, the confidence bounds for "any of the above 3 types," the fourth row of Table 7-3, can be computed by the same technique, merely by using the sums of the injury counts for lacerations and fractures--viz., $i = 53$, $i_1 = 47$, $i_2 = 73$; as before $n = 412$, $n_1 = 4958$, $n_2 = 26,110$, $T = 517,000$. The confidence bounds are that HPR saves from 31,000 to 62,000 AIS 2-4 injuries per year.

In the case of minor lacerations, the effectiveness estimates, E, of 25 percent from Section 4.6 was not based on actual numbers from a particular file but was a heuristic "average" of NCSS and New York results (which, in this case, did not fully agree with one another, whereas they had been very consistent for nonminor injuries). The confidence bounds for the estimate were 5 to 45 percent. They were so large not only for statistical reasons but also to encompass the discrepancy between New York and NCSS. The confidence bounds for the number of injuries, N, in the absence of HPR were based on NCSS, as described above. Since the estimate for E relies heavily on NCSS and for N, entirely, it is again appropriate to make the worst-case assumption that E and N are fully correlated. In other words, apply the lower value of E, 5 percent, to the lower value of N, 439,000 to obtain a lower bound of 22,000 minor lacerations saved--do likewise for the upper bound.

7.3 The number of ejectees through the windshield portal and the benefits of tighter windshield bonding

Section 5.4 provided "best" estimates of the effects of tighter windshield installation methods--adhesive bonding in American cars and clipped rubber gaskets in Volkswagens--on the risk of occupant ejection through the windshield portal. Each of these improvements was found to reduce ejection by about 50 percent. But 70 percent of the fatally or seriously injured occupants who were ejected through the windshield portal actually received their most severe injuries from contacts within the passenger compartment. They would still have been killed or seriously injured even if not ejected. Thus, the tighter installation methods would save the lives of only 15 percent (30% x 50%) of the persons who previously suffered fatal injuries and ejection.

7.3.1 Number of ejectees per year if adhesive bonding and Standard 212 had not been implemented

In order to compute the benefit of tighter windshield installation methods, it is necessary to estimate the numbers of persons per year who were killed or seriously injured and ejected through the windshield portal--during the 1981-83 base period, if the new installation methods had not been implemented. These numbers are multiplied by the casualty-reducing effectiveness (15%) to obtain net benefits.

During 1981-82, there were an average of 18,942 occupant fatalities per year in domestic passenger cars and 1133 in Volkswagens--based on actual counts from FARS 1981-82.

Prior to the changeover from rubber gaskets to adhesive bonding (but subsequent to the door lock improvements of 1965), 25 percent of the fatalities in American cars were ejectees. Prior to Standard 212, but subsequent to the door lock improvements of 1968, 25 percent of Volkswagen fatalities were ejectees. These percentages are based on FARS 1975-82 and confirmed by NCSS data.

Thus, there would have been 4,736 ejection fatalities per year in American cars and 283 in Volkswagens.

Table 5-9 suggests that 39 out of 264 ejections with known ejection portal, or 14.8 percent, were through the windshield portal in American cars with rubber gaskets; 9 out of 54, or 16.7 percent were through the windshield portal of pre-Standard 212 Volkswagens. The statistics are based on combined NCSS and MDAI data.

In other words, there would have been 700 persons (14.8% of 4,736) ejected through the windshield portal and killed, per year, in domestic cars and 47 in Volkswagens (16.7% of 283).

Table 5-10, which is based on NCSS and MDAI data, shows 36 persons ejected through the windshield portal and killed and 55 with serious non-fatal (AIS 3-5) injuries: a ratio of 1.53 seriously injured occupants per fatality.

Thus, the estimated annual numbers of casualties, if American cars still had rubber gaskets and Volkswagens did not meet Standard 212, would be

Ejected through windshield portal and:

killed	-	American cars	700
AIS 3-5	-	American cars	1070
killed	-	Volkswagens	47
AIS 3-5	-	Volkswagens	72

7.3.2 Benefits and their confidence bounds

Adhesive bonding saves 15 percent of the fatalities and serious injuries of persons who would have been ejected through the windshield portal. Table 7-4 applies this percentage to the numbers of casualties that would have occurred with rubber gaskets, resulting in an estimated savings of 105 lives and 160 AIS 3-5 injuries per year in American cars.

In Volkswagens, the casualty-reducing effect of the clips installed in response to Standard 212 is likewise 15 percent, resulting in 7 lives and 11 AIS 3-5 injuries saved per year.

TABLE 7-4

ANNUAL BENEFITS OF TIGHTER WINDSHIELD INSTALLATION TECHNIQUES

		No. of Casualties - Ejected through Windshield Portal	Casualty-Reducing Effectiveness (%)	Casualties Saved
AMERICAN CARS - ADHESIVE BONDING				
	Fatalities	700	15	105
	AIS 3-5	1070	15	160
VOLKSWAGEN - STANDARD 212				
	Fatalities	47	15	7
	AIS 3-5	72	15	11

Confidence bounds are calculated for the estimate of lives saved in American cars, which is by far the most important estimate in Table 7-4. The full formula for benefits was

$$B = NJ_1 \frac{w_1}{j_1} E \frac{x}{k}$$

where B = benefits (lives saved)

N = annual no. of domestic passenger car fatalities (FARS) = 18,942

J_1 = percent of fatalities who are ejectees, rubber gasket cars (FARS) = 25%

W_1 = windshield portal ejectees, rubber gasket cars (NCSS-MDAI) = 39

J_1 = all ejectees (known portals), rubber gasket cars (NCSS-MDAI) = 264

E = ejection reducing effectiveness of adhesive bonding = 50%

x = windshield ejectees with exterior-to-compartment injuries whose AIS was 3-6 and was more severe than their other injuries (NCSS-MDAI) = 17

k = windshield ejectees (AIS 3-6) with known injury sources (NCSS-MDAI) = 55

In turn, E, the ejection reducing effectiveness of 50 percent, was not derived from a single formula but was a judgmental "average" based on the NCSS-MDAI analysis of windshield ejectees per 1000 crash-involved occupants (which suggested a 68 percent effectiveness--see Table 5-8), the

NCSS-MDAI analysis of windshield ejectees relative to other portals (41 percent effectiveness--see Table 5-9), the FARS analysis of ejection (any portal) relative to nonejection (which support a 50 percent effectiveness--see Section 5.3.1) and the NCSS analysis of serious windshield bond separation (48 percent effectiveness--see Section 5.4). But NCSS-MDAI data on ejection obviously was important in determining E. As a result, E cannot be considered independent from w_1.

In order to capture the correlation of E and w_1, let it be assumed that E is derived from a simple analysis of ejection rates per 1000 crash-involved occupants (Table 5-8) except that the number of occupants of cars with adhesive bonding is changed to produce a 50 percent effectiveness estimate:

$$E = 1 - \frac{w_2 / n_2^*}{w_1 / n_1}$$

where E, w_1 are as before

n_1 = occupants of rubber gasket cars (NCSS-MDAI) = 9397

w_2 = windshield portal ejectees, adhesive bonding cars (NCSS-MDAI) = 55

n_2^* = occupants of adhesive bonding cars, modified to yield 50% effectiveness = 26,504

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