NHTSA TECHNICAL REPORT

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AN EVALUATION OF FEDERAL MOTOR VEHICLE SAFETY STANDARDS FOR PASSENGER CAR STEERING ASSEMBLIES

STANDARD 203 - IMPACT PROTECTION FOR THE DRIVER
STANDARD 204 - REARWARD COLUMN DISPLACEMENT

JANUARY 1981

Prepared by:

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An Agency staff review of existing Federal regulations performed in response to Executive Order 12044 and Department of Transportation Order 2100.5.

16. Abstract

Energy absorbing steering columns were installed in passenger cars in response to Federal Motor Vehicle Safety Standard 203. The columns are designed to compress at a controlled rate, cushioning the impact of the driver's chest in frontal crashes. Standard 204 specifies requirements limiting the rearward displacement of the steering wheel toward the driver. The objectives of this Agency evaluation are to determine how many driver fatalities and injuries are prevented by Standards 203 and 204, to measure the actual cost of the standards, to assess cost effectiveness and to describe the actual crash performance of equipment installed in response to the standards. The evaluation is based on statistical analyses of Fatal Accident Reporting System and National Crash Severity Study data, cost analyses of actual steering assemblies and a review of laboratory and crash tests and multidisciplinary accident investigations. It was found that

- o Standards 203 and 204 are cost-effective and have significantly reduced driver fatalities and injuries in frontal crashes. They will annually prevent 1300 fatalities and 23,000 nonfatal injuries requiring hospitalization when all cars comply.
- o Standards 203 and 204 have added $10 to the lifetime cost of owning and operating a car.
- o Energy absorbing steering assemblies have been partially successful in cushioning the driver, but their performance is degraded under nonaxial loads.
- o Standard 204 has substantially reduced rearward displacement of the steering column in crashes.

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METRIC CONVERSION FACTORS

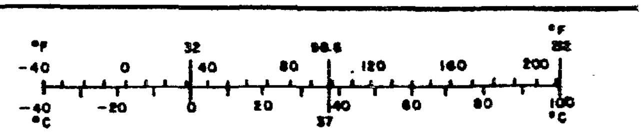
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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* unpublished computer printouts

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LIST OF ABBREVIATIONS

ACIR	Automotive Crash Injury Research
AIS	Abbreviated Injury Scale
AMC	American Motors Corporation
BMDP	Biomedical Programs (P Series)
CDC	Collision Deformation Classification
CRASH	Computer Reconstruction of Accident Speeds on the Highway
df	degrees of freedom
EAD	Energy Absorbing Device
EFU	Equivalent Fatality Unit
ENGS	Expected Net Gain due to Sampling
EVPI	Expected Value of Perfect Information
EVSI	Expected Value of Sample Information
FARS	Fatal Accident Reporting System
FMVSS	Federal Motor Vehicle Safety Standard
GM	General Motors
GSA	General Services Administration
K+A	fatal and serious injuries (police-rated)
MDAI	Multidisciplinary Accident Investigation
MIC	Motors Insurance Corporation
MY	Model Year
NASS	National Accident Sampling System
NCSS	National Crash Severity Study
NHTSA	National Highway Traffic Safety Administration
NPRM	Notice of Proposed Rulemaking

PDOF	Principal Direction of Force
SAE	Society of Automotive Engineers
SAS	Statistical Analysis System
UCLA	University of California at Los Angeles

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The comments and information provided by Agency engineers were especially useful in preparing the evaluation: Ed Jettner and Bill Smith, Rulemaking; Bob Krauss, Enforcement; Lee Stucki, Research and Development; and Bob Lemmer, Plans and Programs.

EXECUTIVE SUMMARY

The steering assembly is the most common source of serious injury for drivers involved in frontal crashes. In passenger cars built before the 1967 model year, the steering column was a rigid pole ending in a narrow hub. In frontal crashes, the driver would hit the rigid column, his load concentrated on the narrow hub. Even worse, in some crashes the steering column was propelled rearwards, toward the driver, at a high rate of speed. Steering wheels and spokes were weak and brittle and contained hazardous metal attachments.

During the 1960's, the motor vehicle manufacturers, in cooperation with the safety research community, developed energy absorbing columns that collapsed at a controlled rate when the driver hit them. Methods were discovered to prevent the rearward displacement of the column in crashes and safer steering wheels were designed. The General Services Administration established criteria for testing the performance of the improved steering assemblies under controlled conditions. These performance criteria became Standard 515/4a for Government vehicles. In 1967, the National Highway Traffic Safety Administration extended the requirements to all passenger cars sold in the United States, effective January 1, 1968. The requirements were promulgated as Federal Motor Vehicle Safety Standards 203 and 204. All passenger cars since model year 1968, as well as many 1967 models, appear to have met the Standards. In addition, the manufacturers have voluntarily made some improvements in the steering wheels that were not strictly required for compliance with the Standards.

Executive Order 12044 (March 1978) and Department of Transportation Order 2100.5 (May 1980) called for a review and evaluation of existing major

regulations. This study is an evaluation of the vehicle modifications made in response to Standards 203 and 204, based on the actual operating experience of passenger cars. The evaluation objectives are

(1) Calculating the overall benefits of the vehicle modifications - life savings and injury severity reduction - treating Standard 203, Standard 204 and the voluntary steering wheel improvements as a single unit.

(2) Measuring the actual cost of the modifications.

(3) Assessing cost-effectiveness.

(4) Comparing the compliance test requirements to the performance of post-Standard vehicles in highway accidents.

(5) Explaining why the Standards have been effective; assessing the benefit for each specific vehicle modification and the mechanism whereby it produces benefits.

(6) Identifying the principal shortcomings of the current Standards - vehicle improvements whose benefits did not meet expectations.

(7) Identifying areas in which Standards 203 and 204 could potentially be improved.

The fatality reduction due to Standards 203 and 204 was estimated by analyzing 5 years of Fatal Accident Reporting System (FARS) data. Statistical analyses of National Crash Severity Study (NCSS) data - 11,840 accident cases were on file as of November 1979 - were performed to determine the number of serious injuries prevented. The Multidisciplinary Accident Investigation (MDAI) file provided information on steering column compression. The cost of Standards 203 and 204 was calculated by analyzing the individual components of a representative sample of steering assemblies.

The results from the FARS, NCSS and MDAI analyses were compared to previously published statistical studies of Standards 203 and 204. Laboratory and crash test results were reviewed, as were clinical analyses of selected accident cases. The research, rulemaking and enforcement activities related to the two Standards were discussed with Agency engineers. The conclusions of this evaluation are based on all of the information sources - statistical, clinical and engineering.

The most important and definitive conclusions of this evaluation are that Standards 203 and 204 have reduced the number of driver fatalities and serious injuries in frontal crashes. Standard 204 has decreased rearward displacement of the steering column. These conclusions are based on statistically significant and consistent findings from a wide variety of data files. The statistical findings, moreover, were uniformly consistent with engineering intuition and clinical analyses.

The findings on some of the detailed analyses, such as the effectiveness of specific types of energy-absorbing devices, were not statistically significant because they involved splitting the data into subsamples. Conclusions based on those findings are less than definitive.

The conclusions on why the Standards have been effective, how much each hardware improvement has contributed to benefits and what could be done to enhance effectiveness must be considered speculative. These conclusions are intuitive judgments based on a thorough review of engineering analyses, selected accident cases, test results and statistical tabulations.

The evaluation suffers from the inherent shortcoming of a "before-after" design. The pre-Standard cars - model year 1967 and earlier - are quite a few years older than the post-Standard cars on the accident data files. A major portion of the analysis was devoted to identifying and removing the resulting biases. Several independent tests which were performed on the data files appear to suggest that the age biases and other confounding factors may have been successfully removed.

The missing data rate on injury-causing contact points was high (30 percent) in the National Crash Severity Study and it varied from one team to another. It was necessary to devise analytic techniques for removing the consequent biases. The NCSS file did not contain information on steering column compression, thereby precluding a rigorous statistical comparison of injury severity and column compression.

In general, though, the findings and conclusions of this evaluation may be viewed with confidence because of the harmony between the statistical results, in-depth findings and engineering intuition. Earlier studies of Standards 203 and 204 were largely consistent with the NCSS, FARS, and MDAI analyses performed for this evaluation. Many of the principal findings were supported by two or more independent analysis procedures or data sources.

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

Principal Findings

The problem

- In 1978, when nearly 90 percent of the passenger car fleet had complied with Standards 203 and 204, 41,400 drivers of passenger cars were killed or hospitalized as a result of contact with the steering assembly during a crash. This number would have increased to 63,000 if the steering assembly improvements required by Standards 203 and 204 had not been made.

Effectiveness and benefits of Standards 203 and 204 - fatalities

- The equipment installed in response to Standards 203 and 204 (including voluntary steering assembly improvements not strictly required for compliance) reduced the overall risk of driver fatality in a frontal crash by 12 percent (confidence bounds: 8.5 to 15.5 percent).

- If all passenger cars had complied with Standards 203 and 204 in 1978, there would have been 1300 fewer driver fatalities than if none of the cars had complied (confidence bounds: 900 to 1800).

Effectiveness and benefits of Standards 203 and 204 - serious injuries

- The equipment installed in response to Standards 203 and 204 reduced the risk of serious injury due to steering assembly contact by 38 percent (confidence bounds: 28 to 48 percent). An injury is defined to be "serious" if it causes the driver's death or at least overnight hospitalization.

- Since 46 percent of the driver fatalities and hospitalizations in frontal crashes were principally due to the steering assembly (i.e., no serious injuries from any other contact source), Standards 203 and 204 reduced the overall risk of serious driver injury in a frontal crash by 17.5 percent (i.e., 46% of 38%).

- If all passenger cars had complied with Standards 203 and 204 in 1978, 24,200 fewer drivers would have sustained serious injury caused by contacting the steering assembly than if none of the cars had complied (confidence bounds: 14,900 to 33,500).

Cost of Standards 203 and 204

- The average lifetime consumer cost per car, for cars built during 1968-78, was:

Modifications needed for meeting the Standards	$ 8.87
Voluntary steering wheel improvements	.33
Fuel consumption due to 1.11 pound weight increase	1.26
TOTAL	$10.46 (in 1978 dollars)

- There were no substantial differences among the principal designs of energy absorbing steering systems in regard to their cost and weight.

Cost-effectiveness

- An "Equivalent Fatality Unit" corresponds to 1 fatality or 20 injuries requiring overnight hospitalization. Standards 203 and 204 eliminate

23.8 Equivalent Fatality Units per million dollars of cost (confidence bounds: 18.2 to 29.4).

Displacement of the steering column into the passenger compartment

- The steering column was displaced rearwards in 18 percent of the pre-Standard cars in which the driver was seriously injured by the steering assembly.

- Standard 204 reduced rearward column displacement by a statistically significant 81 percent.

- The steering column was displaced upwards or sideways in 3 percent of the pre-Standard cars in which the driver was seriously injured by the steering assembly.

- The incidence of gross upward or sideways column displacement in crashes is too low to allow a statistically significant comparison between pre- and post-Standard cars, even though the incidence was observed to be 68 percent higher in the post-Standard cars.

Conclusions

The problem

° Standards 203 and 204 addressed themselves to specific, quantifiable motor vehicle safety problems of major importance.

Overall effectiveness

- The equipment installed or modified in response to Standards 203 and 204 has reduced driver fatalities in frontal crashes.
- It has reduced serious nonfatal injuries to drivers in frontal crashes.
- Standards 203 and 204 are cost-effective.

Why have Standards 203 and 204 been effective?

- Standard 204 has been highly effective in reducing rearward steering column displacement. This factor accounts for about 1/3 to 1/2 of the total injury reduction and an even higher fraction of the total fatality reduction for Standards 203 and 204, combined.
- The energy absorbing devices installed in response to Standard 203 are successfully compressed (3 inches or more) in about half the crashes in which they are heavily impacted by the driver. This factor accounts for about 1/4 to 1/3 of the total injury reduction and an even larger fraction of the total fatality reduction for Standards 203 and 204 combined.
- The improvements to steering wheels that manufacturers voluntarily made at about the time that Standards 203 and 204 took effect – hub padding, removal of horn rings, stronger rims and spokes – have substantially reduced arm and head injuries. They have also contributed to the effective operation of the energy absorbing devices. They account for about 1/3 of the overall injury reduction (but a much smaller fraction of the fatality reduction) for Standards 203 and 204, combined.

- The significant steering assembly contact injury reduction due to Standards 203 and 204 and the successful or partially successful performance as intended, in crashes, by each of the major equipment modifications is proof that the compliance test conditions are relevant to some aspect of actual highway performance.

Shortcomings of Standards 203 and 204

- The principal shortcoming of Standards 203 and 204 has been the failure of the energy absorbing devices to compress in about half the crashes in which they are heavily impacted by drivers.

- Energy absorbing devices and other steering assembly components tend to bind rather than compress when they are exposed to nonaxial loads.

- Nonaxial loads may be a consequence of initial vehicle damage, unfavorable driver kinematics, upward steering column displacement, unfavorable steering wheel spoke alignment or oblique frontal crash forces.

- Standard 204 has not reduced the incidence of steering column displacement in a primarily upwards or sideways direction.

- The improvements to the spokes, rim and face of steering wheels were largely voluntary. Since they are not required for compliance, they have not been uniformly applied to the vehicle fleet.

Side effects of Standards 203 and 204

- The Standards do not appear to have had negative side effects: there was no increase in serious injury from contact points other than the steering assembly.

Comparison of alternative energy absorbing devices

- The six major designs of energy absorbing devices are about equally effective in reducing serious injuries.
- The various devices did not differ substantially in their tendency to bind under driver load.
- They all cost approximately the same.
- A British study concluded that the steering wheel canister is more effective and more easily compressible than the energy absorbing columns. This evaluation does not support their conclusion.

Potential for improving Standards 203 and 204

- There may be potential benefits in extending the Standard 203 requirements, which currently simulate energy absorbing device performance only under nearly axial column load, to include tests that simulate nonaxial loading situations.
- For substantially increased benefits, it may be necessary to realistically simulate many of the conditions that lead to nonaxial loading, such as initial vehicle damage, unfavorable driver kinematics, upward steering column displacement, unfavorable steering wheel spoke alignment and oblique frontal crash forces.
- Upward column displacement, even in small amounts, can aggravate column binding. In larger amounts, it can magnify head injury risk. There may be potential benefits in modifying the requirements of Standards 203 and 204 to reduce both types of hazard associated with upward column displacement.

- The voluntary steering wheel improvements have not been uniformly implemented. There may be potential benefits in adding performance requirements to Standard 203 that would result in the use of crashworthy steering wheels in the entire vehicle fleet.

CHAPTER 1

INTRODUCTION

1.1 Federal Motor Vehicle Safety Standards – the program and its evaluation

The primary goal of the National Highway Traffic Safety Administration is to reduce deaths, injuries and damages resulting from motor vehicle accidents. The Federal Motor Vehicle Safety Standards are one of NHTSA's principal safety programs. Each standard requires certain types of new motor vehicles or motor vehicle equipment sold in the United States to meet specified safety performance levels. Over 50 standards, affecting cars, trucks, buses, motorcycles or aftermarket parts, have been issued since 1966.

The National Traffic and Motor Vehicle Safety Act of 1966 [57], which provides the authority to issue safety standards, specifies that each standard shall be "practicable," "meet the need for motor vehicle safety" and "provide objective criteria." It defines "motor vehicle safety" to mean protection against "unreasonable" risk of accidents, deaths or injuries. Thus, to meet the requirements of the Act, a standard must:

(1) Incorporate performance tests that can be carried out under controlled conditions. The test conditions are relevant to some aspect of actual highway performance.

(2) Address a specific motor vehicle safety problem.

(3) Be within the financial capability of manufacturers.

The Federal Motor Vehicle Safety Standards set minimum performance requirements but do not specify the design of safety equipment. Manufacturers may choose any design that meets or, for that matter, exceeds the minimum requirements. They may provide additional safety equipment which generally mitigates the highway safety problem addressed by the standard but is not actually needed to meet the specific compliance test requirements.

The Government, the motor vehicle manufacturers and independent researchers have contributed to the development of motor vehicle standards. In the case of the early (1968) standards especially, it was the motor vehicle industry that conducted or sponsored much of the research and sought self-regulation through the Society of Automotive Engineers' Recommended Practices. The Government subsequently promulgated performance requirements that many vehicles were already meeting or exceeding.

In 1975, the NHTSA Administrator directed the Office of Program Evaluation to evaluate existing Federal Motor Vehicle Safety Standards [43]. The specific objectives of each evaluation were:

(1) To determine if a standard was actually performing as intended.

(2) To determine benefits and costs and to assess cost-effectiveness.

Executive Order 12044, dated March 23, 1978 and titled "Improving Government Regulations," called for a Government-wide review of existing regulations [18]. It sets forth a policy that regulations be as simple and clear as possible and that they achieve legislative goals effectively and efficiently, without imposing unnecessary burdens on the economy, or individuals, or public or private organizations, or State and local governments. Agencies are to periodically review their existing regulations to determine whether the policy goals of Executive Order 12044 are being achieved.

The Secretary of Transportation issued, on February 26, 1979, a Departmental "Statement of Regulatory Policies and Procedures" to implement the requirements of Executive Order 12044 [25]. This statement was superseded by Department of Transportation Order 2100.5, dated May 22, 1980 and titled "Policies and Procedures for Simplification, Analysis, and Review of Regulations." The Department publishes a "Semiannual Regulations Agenda and Review List" that shows which evaluations are in progress or planned and their target completion dates [26]. A Federal Register Notice, published by NHTSA on July 10, 1980, solicits public views on NHTSA's motor vehicle safety and fuel economy standard evaluations, particularly on which Standards should receive priority consideration for evaluation [27].

The first evaluation published by NHTSA in response to the 1975 and 1978 directives was An Evaluation of Standard 214 - Side Door Strength [37]. The report appeared in September 1979 and was a preliminary one based on an accident data file which was less than half complete at that time. The study covered an assessment of

- overall benefits of Standard 214, using the then available cases in the National Crash Severity Study file and, to a far lesser extent, the Fatal Accident Reporting System
- cost of Standard 214, based on detailed teardown analyses of pre- and post-Standard vehicles.
- cost-effectiveness, using a variety of statistical techniques, but not using societal benefit/cost ratios.

NHTSA invited public review of the evaluation and comments were placed in Docket 2-6, Notice 9.

The comments received on the Standard 214 evaluation, during the internal NHTSA review as well as subsequent to publication, may be summarized as follows:

(1) The general procedures used in assessing benefits, cost and cost-effectiveness were appropriate and may be used for many other standards.

(2) When possible, the evaluation of benefits should be broadened to include statistical analyses of more than one data file, reviews of previous effectiveness studies and assessments of effectiveness in laboratory tests, crash tests and clinical accident investigations.

(3) In addition to calculating the overall benefits, try to explain why a standard has been effective (or ineffective). Compare each major statistical finding to expectations based on engineering judgment, testing or clinical analysis and provide an engineering explanation for observed discrepancies. This will make the evaluation a more useful tool for guiding possible future rulemaking activity.

(4) The benefits attributed to Standard 214 were, perhaps, due in part to side impact crashworthiness improvements which were not strictly needed to meet the performance requirements of the standard. The cost analysis, on the other hand, was mainly limited to the side door beam, which was required for compliance. The cost analysis should be expanded to include some of the other improvements or, alternatively, the effects of some of the other improvements should be controlled for and removed during the statistical analysis of benefits.

(5) More detailed backup documentation should have been provided.

The comments have helped delineate NHTSA's evaluation mission. They have been carefully considered in the preparation of this report.

1.2 Why evaluate Standards 203 and 204?

Federal Motor Vehicle Safety Standards 203 and 204, which became effective for passenger cars manufactured after January 1, 1968, aim to prevent driver fatalities and injuries resulting from contacting the steering assembly. Standard 203 specifies maximum force levels during a laboratory test that simulates driver contact with the steering wheel in a frontal crash [23]. Steering systems that comply with the standards are designed to yield forward or telescope in a collision, cushioning the impact of the driver's chest by absorbing much of the impact energy. Standard 204 specifies limits for rearward displacement of the steering wheel into the passenger compartment during a staged collision [23].

The basic research and development preceding the promulgation of Standards 203 and 204 was, for the most part, conducted or sponsored by the motor vehicle industry. The Saginaw Steering Gear Division of General Motors pioneered the design of energy absorbing steering systems. By model year 1967, Saginaw was supplying energy absorbing steering assemblies for GM, Chrysler and AMC cars.

The first Federal regulation on steering assemblies was the General Services Administration's Standard 515/4a, which applied to Federally purchased vehicles [21]. NHTSA adopted the language of this standard, almost verbatim, and created 2 Federal Motor Vehicle Safety Standards from it: Standard 203, which contains the clauses pertaining to energy absorption and Standard 204, which contains the clauses pertaining to rearward column displacement.

Thus, although Standards 203 and 204 are 2 separate NHTSA regulations, they spring from a single GSA standard and a unified research and development effort. The principal hardware modification in many cars – the energy absorbing steering column with shear capsule – plays a role in the compliance tests for both Standards. There are no vehicles known to comply with one of the standards but not the other. For these reasons, Standards 203 and 204 will be treated as a single standard for the purpose of this evaluation and their benefits and costs will be jointly estimated.

Furthermore, as a consequence of their problem identification and design work, the manufacturers made several steering assembly improvements that were not strictly required to meet the compliance tests for Standards 203 and 204. These voluntary improvements – primarily concerning the steering wheel and spokes – more or less coincided with the hardware changes actually needed for compliance. They have improved the crashworthiness of steering assemblies and are designed to work in tandem with the hardware changes strictly needed for compliance. For these reasons, the benefits and costs of the voluntary improvements will be treated, in this evaluation, as part of the benefits and costs of Standards 203 and 204.

The main reason that Standards 203 and 204 were given high priority for evaluation is that they address an exceptionally serious safety problem: the steering assembly is the most common injury producing contact point for drivers in frontal crashes. More drivers are killed or seriously injured in frontal impacts than in any other type of crash. There are more fatalities and serious injuries to passenger car drivers than to occupants of any other seat position, because the other seat positions are often unoccupied.

A second reason for the evaluation is the continued ambivalence of the highway safety research community toward Standards 203 and 204, despite or perhaps because of the multitude of attempts to evaluate them. Initial analyses of energy absorbing steering column performance in highway accidents generally showed a high level of effectiveness, both in statistical terms and in clinical reviews of individual accidents [33], [34], [45], [56], [65]. Before long, it was found that the energy absorbing device often does not compress in crashes [45], [65]. The finding resulted in doubts about whether the standards were accomplishing their goals, even though studies continued to appear that showed fairly high effectiveness [44], [50], [58], [62]. In the early 1970's, 3 controversial reports claimed that the energy absorbing steering column was not effective in the field [5], [29], [30]. Some of the subsequent research was aimed at explaining why it might not be effective [28]. By the mid-1970's, the highway safety research community was perplexed [36]. Even though the issue of effectiveness was undecided, few analyses of the Standards appeared after 1975. It seems that the research community had set the issue aside.

Nevertheless, Standards 203 and 204 are two of the most important safety standards that NHTSA has promulgated. It is therefore appropriate for the Agency to find out how well the standards have performed.

The final reason for performing the evaluation at this time is that two major new data files have become available and are large enough so that statistically meaningful results can be obtained: the National Crash Severity Study and the Fatal Accident Reporting System. The files provide information that is quantitatively and qualitatively better than what was available for the earlier analyses. There is a further reason for conducting the evaluation now. Since pre-Standard 203 and 204 cars (model year 1967 and earlier) are now vanishing from the highways, the number of NHTSA-investigated accidents involving those cars will be small in the future compared to the number of them already on the files. In other words, NHTSA has just about all the data it will ever acquire on the pre-Standard cars.

1.3 Contents of the evaluation

Chapter 2 summarizes the evaluation findings and conclusions. Section 2.1 is a capsule summary of the principal findings. Each of the findings is then discussed in greater detail in Sections 2.2 - 2.5, with selected tabulations; Section 2.2 deals with problem definition; Section 2.3 discusses the overall effectiveness of Standards 203 and 204; cost and cost-effectiveness are the topics of Section 2.4; Section 2.5 examines why the Standards have been effective and in what areas they have performed especially well or poorly. Finally, Section 2.6 presents the study's conclusions.

Chapter 3 is a review of the problem - driver injuries and fatalities involving contact with the steering assembly - and of Standards 203 and 204. Sections 3.1 - 3.3 deal with problem definition: the numbers and severity of injuries that occurred in pre-Standard cars, the role of steering column intrusion and the types of injury mechanisms experienced by drivers. Section 3.4 gives a research and regulatory history of Standards 203 and 204 and describes the various hardware improvements made in post-Standard steering assemblies, including those not strictly required for compliance with the standards.

Section 3.5 discusses the problem and the Standards from an engineering viewpoint: why were the post-Standard steering assemblies designed the way they were and why are the designs expected to protect drivers in crashes? Section 3.6 briefly reviews some of the other Federal Motor Vehicle Safety Standards that protect drivers in frontal crashes.

Section 3.7 provides a pictorial review of Standards 203 and 204, including photographs of pre-Standard steering assembly performance in crashes, drawings and photos of the hardware improvements, and photos of successful and unsuccessful post-Standard steering assembly performance in crashes.

Chapter 4 discusses the procedure used for estimating the full consumer cost of Standards 203 and 204 and presents the results. The full cost includes cost of hardware installed to meet the compliance tests, voluntary hardware improvements in the steering assembly that more or less coincided with Standards 203 and 204, and additional lifetime fuel consumption due to weight added to cars by the Standards.

Chapter 5 is devoted to estimating the overall effectiveness of Standards 203 and 204. Section 5.1 reviews effectiveness estimates in earlier studies. Section 5.2 reports and documents the fatal-and-serious injury reduction estimate based on National Crash Severity Study data. Section 5.3 presents the fatality reduction found in the Fatal Accident Reporting System. Cost-effectiveness of Standards 203 and 204 is examined in Section 5.4. The results of Chapter 5 are summarized in Section 5.5.

Chapter 6 takes a closer look at "why" the Standards have been effective as well as the areas in which they are deficient. It consists of a set of more detailed effectiveness analyses concerning certain aspects of the Standards: intrusion reduction (Section 6.1), effectiveness of alternative energy absorbing steering system designs (6.2), injury reduction by body region (6.3), possible negative secondary effects of Standards 203 and 204 (6.4), failure of energy absorbing devices to compress (6.5) and effectiveness under various crash conditions (6.6 - 6.9). Section 6.10 ties together the individual analyses in a summary discussion of why the Standards have been effective.

The Appendices contain the computer runs that supported the evaluation analyses.

1.4 Strengths and weaknesses of the evaluation

The limitations and vulnerable areas of the evaluation are the following:

(1) The evaluation suffers from the inherent shortcoming of a "before-after" design - i.e. the post-Standard cars are generally newer than the pre-Standard cars. In particular, the pre-Standard cars (model 1967 and earlier) are quite old in the National Crash Severity Study (NCSS - collected 1977-79) and the Fatal Accident Reporting System (FARS - collected since 1975). That shortcoming, however, is thought to be minimal in this evaluation because of the evidence (Section 5.2.4) that there are few vehicle age-related biases in the data other than the ones that were controlled for by analytic techniques.

(2) The NCSS file, although large enough for a precise estimate of overall effectiveness and intrusion reduction, was not large enough for statistically precise results on some of the analyses of Chapter 6.

(3) There is a high rate of missing data on contact points in NCSS (30 percent of hospitalized drivers). The NCSS analysis relies heavily on contact point information. Moreover, the incidence of missing contact points differs significantly

from one NCSS team to another. It became necessary to use "NCSS team" as a control variable in the analysis.

(4) The NCSS file does not contain a measurement of energy absorbing device compression. It was necessary to rely on Multidisciplinary Accident Investigation data in performing the analysis of failures to compress. If NCSS had contained compression data, it would have been possible to compare compression to injury reduction and reach more definitive conclusions in Chapter 6.

(5) FARS does not contain contact point information. An indirect technique had to be used for measuring fatality reduction due to Standards 203 and 204.

The strong points of the evaluation are the following:

(1) The scope of the evaluation included statistical analysis of accident data, review of in-depth accident investigations, test results and engineering analysis. There was a high degree of consistency between the statistical results and the engineering and clinical analyses.

(2) There was a high degree of consistency between NCSS results, FARS results and 6 out of 7 statistical studies. They all showed significant effectiveness for Standards 203 and 204. The only study which did not show significant overall effectiveness can be suspected of containing serious biases. The overall effectiveness was observed to be of roughly equal magnitude in NCSS, FARS and the 6 earlier studies.

(3) The NCSS and FARS data sets were large enough for a high degree of statistical precision in the estimates of overall injury and fatality reduction.

(4) The cost analysis was not limited to hardware improvements strictly required for compliance with the Standards, but included voluntary improvements which enhanced steering assembly crashworthiness. In other words, it was attempted to put the cost and benefit analyses on a consistent basis.

(5) Effectiveness in the NCSS analysis was defined to be the reduction of the steering assembly contact injury rate. This minimized the likelihood of attributing injury reductions to Standards 203 and 204 which were actually due to improved windshields, padded dash boards, or other improvements.

(6) Two analyses, which were performed as a check, provided a high degree of confidence that the injury reductions attributed to Standards 203 and 204 are real and are not the result of an "age effect" or biases on the NCSS file. (The analyses were the inspection of time trends in the steering assembly contact injury rate and of changes in the non-steering assembly contact injury rate - see Section 5.2.4.)

(7) The modelling technique used with the NCSS data to control for confounding factors was empirical - it clearly showed at each stage the magnitude of confounding effects. It also allowed for the inspection of a large number of potential confounding factors.

(8) The techniques for calculating confidence bounds - the jackknife technique for NCSS and subsampling of FARS - were empirical. The use of complicated estimation formulas, adjustment factors, approximations and assumptions was avoided as much as possible. Moreover, the NCSS confidence bounds were checked by using a conservative estimation technique (viz., treating the 7 teams as randomly selected clusters).

(9) The injury criterion used with NCSS – fatality or transport-and-hospitalization – led to substantial reductions in sampling error relative to what would have occurred with AIS-based injury rates. More importantly, it reduced the likelihood of spuriously "significant" results in the detailed analyses of Chapter 6.

(10) The successful use of FARS – a national census containing over 100,000 fatalities – for the estimate of fatality reduction is preferable to basing the estimate on the small number of fatals that occur on a non-fatal file or assuming that the fatality reduction is "about the same" as the serious injury reduction.

In view of the weaknesses and strengths of various portions of the evaluation, the findings may be characterized as follows:

. The findings on overall effectiveness and intrusion reduction for Standards 203 and 204 may be considered <u>definitive</u>. They can also be called <u>final</u> to the extent that few additional pre-Standard car accidents will be investigated in the future.

. The findings on some of the detailed analyses – effectiveness of alternative system designs, injury reduction by body region, PDOF, Delta V, etc. – are less than definitive. When the NCSS file is subdivided, the individual subsamples are often too small for statistically significant differences.

. The conclusions on <u>why</u> the Standards have been effective and how much each hardware improvement has contributed should be considered <u>speculative</u>. This also holds true for the conclusions on why the columns sometimes fail to compress and what might be done to enhance compression. These conclusions are intuitive judgments based on a thorough review of engineering analyses, selected accident cases, test results and statistical tabulations.

CHAPTER 2

FINDINGS AND CONCLUSIONS

The results from the evaluation of Standard 203 (Impact Protection for the Driver from the Steering Control System - Passenger Cars) and Standard 204 (Steering Control Rearward Displacement - Passenger Cars) are presented in this chapter. The findings are based on statistical analyses of 11,840 National Crash Severity Study (NCSS) accident cases and 5 years of Fatal Accident Reporting System (FARS) data; a component cost analysis of a representative sample of vehicles; a review of the literature pertaining to laboratory and crash test results, clinical analyses of selected accident cases and statistical analyses of accident data; and discussion with engineers about the research, rulemaking and enforcement activities related to the 2 Standards.

2.1 Principal statistical findings

The problem

- In 1978, when nearly 90 percent of the passenger car fleet had complied with Standards 203 and 204, 41,400 drivers of passenger cars were killed or hospitalized as a result of contact with the steering assembly during a crash. This number would have increased to 63,000 if the steering assembly improvements required by Standards 203 and 204 had not been made.

- Deaths and hospitalizations due to contact with the steering assembly (with or without serious injuries from other contact points) account for 58 percent of the casualties suffered by drivers of pre-Standard cars in frontal crashes. They represent 26 percent of all pre-Standard passenger car occupant deaths and hospitalizations in all types of crashes.

- Of the 63,000 drivers who would have been killed or hospitalized due to contact with the steering assembly, 13,000 would also have suffered serious injury due to other contact sources; 50,000 drivers would have been killed or hospitalized primarily due to the injuries resulting from steering assembly contact. (This represents 46 percent of the drivers in frontal crashes who were killed or hospitalized.)

- Isolating steering assembly contact fatalities from the deaths plus hospitalizations combined grouping was not possible. They are projected to be in the 3000-5000 range.

Effectiveness and benefits of Standards 203 and 204 - fatalities

- The equipment installed in response to Standards 203 and 204 (including voluntary steering assembly improvements not strictly required for compliance) reduced the overall risk of driver fatality in a frontal crash by 12 percent (confidence bounds: 8.5 to 15.5 percent).

- If all passenger cars had complied with Standards 203 and 204 in 1978, there would have been 1300 fewer driver fatalities than if none of the cars had complied (confidence bounds: 900 to 1800).

Effectiveness and benefits of Standards 203 and 204 - serious injuries

- The equipment installed in response to Standards 203 and 204 (including voluntary steering assembly improvements) reduced the risk of serious injury due to steering assembly contact by 38 percent (confidence bounds: 28 to 48 percent). An injury is defined to be "serious" if it causes the driver's death or overnight hospitalization.

- Since 46 percent of the driver fatalities and hospitalizations in frontal crashes were principally due to the steering assembly (i.e., no serious injuries from any other contact source), Standards 203 and 204 reduced the overall risk of serious driver injury in a frontal crash by 17.5 percent (i.e., 46% of 38%).

- If all passenger cars had complied with Standards 203 and 204 in 1978, 24,200 fewer drivers would have sustained serious injury caused by contacting the steering assembly than if none of the cars had complied (confidence bounds: 14,900 to 33,500).

Cost of Standards 203 and 204

- The average lifetime consumer cost per car, for cars built during 1968-78, was:

Modifications needed for meeting the Standards	$ 8.87
Voluntary steering wheel improvements	.33
Fuel consumption due to 1.11 pound weight increase	1.26
TOTAL	$10.46 (in 1978 dollars)

- There were no substantial differences among the principal designs of energy absorbing steering systems in regard to their cost and weight.

Cost-effectiveness

- An "Equivalent Fatality Unit" corresponds to 1 fatality or 20 injuries requiring overnight hospitalization. Standards 203 and 204 eliminate 23.8 Equivalent Fatality Units per million dollars of cost (confidence bounds: 18.2 to 29.4).

Displacement of the steering column into the passenger compartment

- The steering column was displaced rearwards in 18 percent of the pre-Standard cars in which the driver was seriously injured by the steering assembly.

- Standard 204 reduced rearward column displacement by a statistically significant 81 percent.

- The steering column was displaced upwards or sideways in 3 percent of the pre-Standard cars in which the driver was seriously injured by the steering assembly.

- The incidence of gross upward or sideways column displacement in crashes is too low to allow a statistically significant comparison between pre- and post- Standard cars, even though the incidence was observed to be 68 percent higher in the post-Standard cars.

- The effectiveness of Standard 204 in reducing the incidence of column displacement into the passenger compartment, by crash velocity change (Delta V) was:

Delta V (mph)	Effectiveness of Standard 204 (%)
1 - 14	88
15 - 29	62
30+	39

Effectiveness of alternative energy absorbing devices

- The observed effectiveness (reduction of serious injuries due to steering assembly contact) of the principal designs used for energy absorbing steering systems was:

Type	Effectiveness (%)
Mesh column	27
Ball column	36
Slotted column	39
Grooved column	39
Slotted jacket & mandrel	52
Steering wheel canister	23

- The differences in effectiveness among the designs were not statistically significant.

Body regions injured by contact with the steering assembly

- The distribution of steering assembly contact injuries, by body region, was:

Body region	Percent of Fat./Hosp. Injuries	Percent of Fat./Hosp. Injuries with AIS ≥ 3
Chest	41	52
Head/neck	28	9
Abdomen/pelvis	20	28
Arms/legs	13	11

- The effectiveness of Standards 203 and 204 in reducing serious injuries due to steering assembly contact, by body region, was:

Body region	Effectiveness of Stds. 203/204 (%)
Chest	28
Head/neck	45
Abdomen/pelvis	22
Arm/leg	42

- The differences in effectiveness of Standards 203 and 204 among the body regions were not statistically significant.

Effect on injuries due to contacts other than the steering assembly

- The risk of contacting the steering assembly and sustaining a serious injury from another component was 9 percent lower in post-Standard cars than in pre-Standard cars. The reduction is not statistically significant.

Compressibility of energy-absorbing devices

- The ratio of successful device compression under heavy load (at least 3 inches of shear capsule separation) to unsuccessful compression (severely deformed or broken wheel or spokes with less than 1 inch of shear capsule separation) was 47:53.

- The ratio was better than 50:50 for the ball type column but not for any of the other energy absorbing steering assembly designs.

- The ratio of successful compression to unsuccessful compression, by direction of crash force, was:

Direction of force	Ratio of successes to failures
within 15^{0} of longitudinal	50:50
more than 15^{0} lateral component	39:61

Role of the principal direction of crash force

- The distribution of steering assembly contact injuries in pre-Standard cars, by direction o crash force, was:

Direction of force	Percent of injuries	Percent of frontal crashes
within 15° of longitudinal	77	56
more than 15° lateral component	23	44

- The risk of steering assembly contact injury was nearly 3 times higher in direct frontal crashes (within 15 degrees of longitudinal) than in oblique frontal crashes.

- The effectiveness of Standards 203 and 204 in reducing serious injuries due to steering assembly contact was:

Direction of force	Effectiveness (%)
within 15^{0} of longitudinal	39
more than 15^{0} lateral component	12

- The observed difference of effectiveness was not statistically significant.

Effectiveness of Standards 203 and 204 by crash velocity change (Delta V)

- The effectiveness of Standards 203 and 204 in reducing serious injuries due to steering assembly contact was:

Delta V (mph)	Effectiveness (%)
1 - 9	34
10 - 19	32
20 - 29	44
30+	32

- The differences in the observed effectiveness were not statistically significant.

2.2 Discussion of findings: the problem

Standards 203 and 204 were promulgated in order to protect passenger car drivers when they contact the steering assembly in frontal crashes. This assembly consists of the steering wheel rim, spokes, hub, column and supporting structures.

The pre-Standard steering assembly constituted a threefold safety hazard to drivers in frontal crashes: (1) The column was a rigid pole ending in a narrow hub, attached to the steering wheel by narrow, brittle spokes. When the driver moved forward into the wheel after a frontal impact, the wheel and spokes would bend away or break off and the driver would hit the rigid column, his load concentrated on the narrow hub. (2) The column was rigidly linked to the car's frontal structure. In a severe frontal crash, the rearward deformation of the frontal structure pushed the column upwards and to the rear, towards the driver, at a high speed. (3) The brittle, unpadded steering wheel, hub and spokes, and the horn rings and other metal attachments were sources of facial and other injuries. (See Sections 3.3.2 and 3.5 and Figures 3-1 - 3-12, 3-22, and 3-23.)

The starting point for this evaluation is, then, to determine how many deaths and injuries there would be due to steering assembly contact by passenger car drivers in frontal crashes without Standards 203 and 204. Specifically, how many deaths and injuries would there have been in the United States during the base year for this evaluation - 1978 - if these 2 Standards had not been promulgated (but the accident environment was otherwise that of 1978)? Table 2-1 shows the distribution of casualties in this hypothetical baseline situation. The distribution of fatalities and hospitalizing injuries is derived from National Crash Severity Study (NCSS) data by a procedure described in Sections 3.1.2 and 5.2.4. The fatality distribution is derived from Fatal Accident Reporting System (FARS) data by a procedure described in Section 5.3.2. Neither FARS nor NCSS provide usable contact point distributions for fatal accidents involving pre-Standard cars, so no estimates of fatal injury sources were made in Table 2-1. But it is reasonable to assume that the fatality distribution is similar to the serious injury distribution except that, perhaps, it may contain more cases of multiple contact and non-steering assembly contact (see Section 3.1.2).

Table 2-1 shows that a total of 63,100 drivers would have been killed or hospitalized by steering assembly contact (with or without other contacts) in frontal crashes. This represents 58 percent of all driver fatalities and serious injuries in frontal

TABLE 2-1

BASELINE CASUALTIES IN 1978

(If Standards 203 and 204 had not been promulgated)

	Fatalities	Fatalities and Hospitalizing Injuries
All passenger car crashes	29,600	240,000
Passenger car drivers	19,600	160,000
Drivers in frontal crashes	10,900	108,800
Death/hospitalization due to:		
Steering assembly contact only	unk.	50,400
Steering & other contacts	unk.	12,700
Other contacts only	unk.	45,700

crashes and 26 percent of all passenger car occupant fatalities and serious injuries. There would have been 50,400 drivers killed or hospitalized solely as a result of an impact into the steering assembly (i.e., they had no injury from other contact sources that required hospitalization). These cases represented 46 percent of all driver fatalities and serious injuries in frontal crashes.

2.3 Discussion of findings: effectiveness and benefits

The manufacturers responded to Standards 203 and 204 with a threefold program of equipment modifications to reduce the safety hazard to drivers in frontal crashes: (1) The rigid column was replaced by an assembly containing a telescoping, energy-absorbing section which was designed to collapse at a controlled rate when the driver contacts the wheel, limiting the maximum force experienced by the driver. This improvement was required to meet the compliance test for Standard 203. (2) The column contains sections that telescope, buckle or articulate, so that rearward deformation of the car's frontal structure is not translated into rearward displacement of the steering wheel into the occupant compartment. This improvement was required for compliance with Standard 204. (3) The steering wheel, hub and spokes were improved. The wheel was made smaller in diameter, thicker, stronger and less brittle. The spokes were strengthened and widened or increased in number. The hub was padded and in some cars became an integral part of the spokes. Horn rings and metal attachments were removed. The purpose of the steering wheel improvements was to reduce the risk of facial injuries and to spread the driver's load over a larger area. These improvements were by and large voluntary responses – i.e., coincident with, but not strictly required for compliance with a standard – although they may have been partially related to the requirements of Standard 203. (See Sections 3.4 and 3.5 and Figures 3-13 – 3-32.)

The effectiveness of Standards 203 and 204 is determined by calculating the risk of death or injury due to steering assembly contact for drivers of pre-Standard cars involved in frontal crashes. The corresponding risk is calculated for the post-Standard car drivers. The difference in injury risk, to the extent that it is due to equipment installed in response to Standards 203 and 204, is the effectiveness. (See Section 5.2.2.)

The benefits of Standards 203 and 204 were defined to be the reduction in casualties that would have occurred in the United States in the base year, 1978, if all passenger cars had met the Standards relative to those that would have occurred if no cars had met Standards 203 and 204. The benefits are calculated by multiplying the effectiveness by the baseline casualties shown in Table 2-1. (The detailed procedure for calculating benefits is described in Sections 5.3.2 and 5.2.4.)

Fatality-reducing effectiveness and benefits were estimated using Fatal Accident Reporting System (FARS) data. Contact point information is not included in FARS, so fatality risk due to steering assembly contact could not be directly calculated. Instead, the risk reduction was indirectly obtained by comparing driver frontal fatalities in 1966 (pre) and 1968 (post) model cars to a control group of fatalities in 1966 and 1968 model cars that would not have been affected by Standards 203 and 204. (See Section 5.3.1.) Two control groups were used: passenger frontal fatalities and driver side-and-rear-impact fatalities. The results for the two control groups were similar and they were averaged. The results were checked by including 1965 and 1969 model cars in the pre- and post-Standard groups, respectively, and the results were again similar. (See Section 5.3.2.)

Table 2-2 shows the significant life-saving effectiveness and benefits estimated for Standards 203 and 204. The Standards reduced the risk of driver fatality in a frontal crash by 12 percent. They would have saved 1300 lives in 1978 if all passenger cars had been equipped with the improved steering assemblies.

The confidence bounds for effectiveness and benefits (one-sided $\alpha = .05$) were estimated by an empirical procedure. The 5 years of FARS data were construed as 5 independent subsamples. Effectiveness and benefits were calculated separately for each year of FARS and the variation from year to year was observed (see Section 5.3.3).

TABLE 2-2

FATALITY REDUCTION FOR STANDARDS 203 AND 204

Measure	Estimated Effectiveness/Benefits	Confidence Bound Lower	Confidence Bound Upper
(a) Effectiveness			
Driver fatality reduction in frontal crashes	12%	8½%	15½%
(b) Benefits			
Lives saved in 1978 (all cars comply vs. no cars comply)	1300	900	1800

Injury-reducing effectiveness and benefits were estimated using National Crash Severity Study (NCSS) data. Since contact-point information is available on NCSS, it was possible to directly calculate the injury risk due to steering assembly contact.

For this evaluation, a NCSS driver involved in a frontal crash was "seriously injured" if he had an injury due to steering assembly contact which was fatal or necessitated his transport from the accident scene followed by overnight hospitalization. "Fatality or hospitalization" was chosen as the injury criterion because it improves the statistical reliability of NCSS results and also because it is tangible and easily understood (see Section 5.2.1).

The NCSS file used for this evaluation was a stratified simple random sample. There were 4 strata and the sampling fractions were 100, 25, 10 and 5 percent, respectively. NCSS data counts used for calculating injury rates are "weighted" counts: each accident case is multiplied by the inverse of the sampling fraction. Thus, the weighted data counts shown in NCSS tabulations overstate the actual sample sizes. A more reliable impression of the sample size is gained by examining the unweighted as well as the weighted counts (see Section 5.2.1).

In this evaluation, however, all "injured" drivers were in the 100 percent sampling stratum, due to the way the injury criterion was defined. As a result, the weighted and unweighted counts of injured drivers are equal. Only for the uninjured drivers is the weighted count larger than the unweighted count.

The NCSS file used for this evaluation contains 3951 (weighted) or 973 (unweighted) drivers of pre-Standard cars in frontal towaway crashes, of whom 124 (unweighted) received serious injuries from the steering assembly; there are 31,659 (weighted) or 7119 (unweighted) drivers of post-Standard cars in frontal towaways of whom 654 (unweighted) had serious injury from the steering assembly. (See Appendices A and B.) The relatively large sample made it possible to apply statistical modelling techniques in a meaningful way.

The objective was to determine the difference of injury risk, between pre-Standard and post-Standard car drivers, that was due to equipment installed in response to Standards 203 and 204. To achieve the objective, it was necessary to search for and remove the effect of other variables that are correlated with Standards 203/204 compliance and injury risk (sources of bias). Ten variables were selected as potential controls. One of them was "NCSS Team": the missing data rate on contact points(which affects contact-point-related injury rates) and the average age of cars varied significantly from team to team (see Section 5.2.1). It was necessary to use "NCSS Team" as a control variable in order to remove the bias in the overall injury rate that resulted from the team-to-team differences.

The procedure for testing and selecting control variables was empirical, showing at each step the bias removed by using the control variable (see Section 5.2.4). The control variables that were found most important were NCSS Team, Principal Direction of Force, and Driver Age. Controlling for the first of these raised the effectiveness estimate for Standards 203 and 204 by 7 percent; adding the other 2 variables brought the estimate back down by 4 percent. After controlling for these 3 variables, the sum of residual biases due to the other 7 potential controls was very small (on the order of perhaps 1 percent total). Thus, the estimate of effectiveness, controlling for NCSS Team, Principal Direction of Force and Driver Age, was felt to be an unbiased estimate of the injury reduction actually due to equipment installed in response to Standards 203 and 204. This is the estimate of effectiveness shown in Table 2-3. The benefits were derived from the effectiveness estimate, using formulas in Section 5.2.4.

TABLE 2-3

SERIOUS INJURY REDUCTION FOR STANDARDS 203 AND 204

Measure	Estimate of Effectiveness/Benefits	Confidence Bound Lower	Confidence Bound Upper
(a) Effectiveness			
Reduction of fatal or hospitalizing steering assembly contact injury risk	38%	28%	48%
(b) Benefits			
Drivers avoiding steering assembly contact fatality or hospitalization in 1978 (all cars comply vs. no cars comply)	24,200	14,900	33,500

Table 2-3 shows the significant injury reduction estimated for Standards 203 and 204. The Standards reduced the risk of fatality or hospitalization due to steering assembly contact injury by 38 percent. If all passenger cars had been equipped with the improved steering assemblies, 24,200 drivers would have escaped fatal or hospitalizing steering assembly contact injury.

Since 46 percent of driver fatalities and hospitalizations in frontal crashes were principally due to the steering assembly (i.e., no serious injuries from any other contact source - see Table 2-1), the 38 percent effectiveness in reducing steering assembly contact injury corresponds to a 17½ percent overall effectiveness in reducing driver fatalities and hospitalizations in frontal crashes.

Two additional NCSS analyses were performed to check for biases in the results (see Section 5.2.4). First, the steering assembly contact injury rate was plotted by model year. Did the rate increase with vehicle age? A regression analysis showed the injury rate time trend to be flat, except for a large drop at the time that cars began to meet Standards 203 and 204 (see Figure 5-1).

In the second analysis, the NCSS data were used to calculate effectiveness by a procedure somewhat like the one used with FARS: the steering assembly contact injury rates were calculated for pre- and post-Standard cars without using the control variables. Next, the injury rates for contacts other than the steering assembly were calculated for pre- and post-Standard cars (a "control group"). The reduction of post-Standard steering assembly contact injury rates relative to the control group was 38 percent - identical to the reduction shown in Table 2-3.

The 2 analyses provide a high degree of confidence that the NCSS results are not biased - i.e., the injury reduction claimed for Standards 203 and 204 is not due to some vehicle age trend, nor are there any reductions in non-steering assembly contact injury "attributable" to Standards 203 and 204.

The confidence bounds for effectiveness and benefits (one-sided $\alpha = .05$) were estimated by an empirical procedure known as the "jackknife technique." The NCSS file was divided into 10 systematic random subsamples of equal size. One of the subsamples was removed and the injury rates were calculated (controlling for NCSS Team, PDOF and Driver Age) for the remaining nine-tenths of NCSS. The subsample was returned, another was removed, and the injury rates recalculated, etc. The variation from subsample to subsample was observed (see Section 5.2.5).

The results from FARS and NCSS are consistent with the findings of 6 previous statistical analyses of the effectiveness of Standards 203 and 204. Table 2-4 compares the results of FARS, NCSS and the 6 earlier analyses. These studies all found statistically significant effects for Standards 203 and 204 (see Sections 5.1.1, 5.1.2 and 5.5). Another report [5], in which the Standards were not found effective, was reviewed and considered to have introduced a serious bias in the way the data were used: the pre-Standard and post-Standard cars largely came from 2 different, statistically incompatible data files (see Section 5.1.3).

2.4 Discussion of findings: cost and cost-effectiveness

The cost of Standards 203 and 204 was measured on the same basis as the benefits. Since benefits were estimated for base year 1978, costs were expressed in 1978 dollars. Since benefits were based on accident data involving cars on the road in 1978, costs were averaged for cars on the road in 1978. Since the benefits of voluntary steering assembly crashworthiness improvements were included (in addition to those required for compliance with the Standards), so were the costs (see Section 4.1).

TABLE 2-4

EFFECTIVENESS OF STANDARDS 203 AND 204
IN FARS, NCSS AND 6 EARLIER STUDIES

Data Source	Injury Criterion	Measure of Effectiveness: Steering Assy. Contact Inj. Red.	Measure of Effectiveness: Overall Driver Frontal Inj. Red.
FARS 1975-79	Fatal		12
NCSS 1977-79	Fatal or hospitalizing	38	17½
Auto. Crash Injury Research 1964-69 [45]	Torso AIS $\geq$ 1	32	
	Head AIS $\geq$ 1	27	
Multidisciplinary-- UCLA 1962-69 [56]	AIS $\geq$ 2	54	
Multidisciplinary-- Michigan & UCLA [62]	AIS $\geq$ 3	45	
North Carolina 1966 & 68 [44]	K+A		14
North Carolina 1971-72[50]	K+A		20
New York State 1968-69 [58]	K+A		24

The "cost of Standards 203 and 204" is the net increase in the lifetime cost of owning and operating an automobile. There have been 3 principal sources of increased cost: (1) Equipment installed in order to meet the compliance tests increased the purchase prices of cars. (2) Voluntary improvements in the crashworthiness of steering assemblies also caused cost increases. (3) The equipment added to the weight of the car and increased its lifetime fuel consumption.

In the NHTSA cost estimation procedure, representative pre-Standard and post-Standard component subsystems are torn down and examined in detail. The consumer cost and weight are estimated for the pre-Standard and post-Standard subsystems. The consumer cost includes materials, labor, tooling, assembly, overhead, manufacturer's and dealer's markups and taxes. The cost of a specific post-Standard model's component subsystem, minus the cost of a corresponding pre-Standard model's subsystem, equals the incremental consumer cost for Standards 203 and 204 in that model. The incremental weight is similarly obtained. Based on the representative sample of post-Standard vehicles examined, the average cost and weight is calculated for cars on the road in 1978 (see Section 4.2).

Three vehicle subsystems were studied and found to have been modified in response to Standards 203 and 204: (1) The steering column assembly. (2) The intermediate shaft between the steering gearbox and the column. (3) The steering wheel and spokes (voluntary improvements). Vehicle front structures were also examined for possible modifications in response to Standard 204, but none were found.

The bulk of the cost of Standards 203 and 204, as well as the only measurable weight change, was in the steering column assembly. Table 2-5 shows the average cost and weight added by Standards 203 and 204, over the sample of cars studied, for each of the 6 major energy absorbing steering system designs.

TABLE 2-5

AVERAGE COST AND WEIGHT ADDED TO STEERING COLUMN ASSEMBLIES BY STANDARDS 203 AND 204 (1978 dollars)

Steering Column Type	Average Cost	Average Weight	Percent of Cars on Road in 1978
Mesh	$ 9.90	1.59	16
Ball	6.92	1.06	48
Slotted	7.24	1.30	15
Grooved	8.47	0.53	13
Slotted/mandrel	10.25	0.62	5
Wheel canister	9.03	1.52	3
WEIGHTED AVERAGE	$ 7.86	1.11 pounds	

The average cost increase for the steering assembly was $7.68 (in 1978 dollars) and weight increased by 1.11 pounds. Table 5-2 shows that none of the steering column types stand apart from the others in terms of cost and weight. Moreover, the small variations form one column type to another may, to some extent, be due to variation among the individual makes and models that were selected for study.

The average cost increase for modifications of the intermediate shaft needed for Standard 204 compliance was $1.01 (in 1978 dollars).

The sum of the costs for the steering column assembly ($7.86) and the intermediate shaft ($1.01) is $8.87. This is the average consumer price increase, for cars on the road in 1978, due to equipment changes required for compliance with Standards 203 and 204.

The average price increase per car for voluntary modifications made in response to Standards 203 and 204 – improvements to the steering wheel, hub and spokes – was $0.33 (in 1978 dollars).

Each pound of weight added to a car results in additional fuel consumption of 1.1 gallons over the lifetime of the average car. Since Standards 203 and 204 added 1.11 pounds to steering column assemblies, they increase lifetime fuel consumption by an average of 1.22 gallons per car. The mid-1980 price of fuel, translated into 1978 dollars, is $1.03 per gallon. Thus, the incremental expenditure for fuel due to Standards 203 and 204 is $1.26 (in 1978 dollars) over the life of the car.

The total lifetime consumer cost increase, which is the sum of the individual cost elements, averaged $10.46 (in 1978 dollars) per car, for cars on the road during 1978. The cost elements are summarized in Table 2-6.

TABLE 2-6

AVERAGE COST PER CAR FOR STANDARDS 203 AND 204
(1978 dollars)

Item	Cost	
Steering column changes	$7.86	
Intermediate shaft changes	1.01	
REQUIRED FOR COMPLIANCE		$8.87
Steering wheel changes (Voluntary)		.33
Weight added to steering column (1.11 pounds @ $1.136)		1.26
	TOTAL	$10.46

Under the assumption that 10 million passenger cars are sold annually in the United States, the cost of Standards 203 and 204 is about $105 million per year.

The cost-effectiveness of Standards 203 and 204 is the number of Equivalent Fatality Units (EFU) that they eliminate per million dollars of cost. The EFU is a single quantity that measures the number of lives saved and injuries prevented by the Standards: each life saved by Standards 203 and 204 is a benefit of 1 EFU. Each person who avoids nonfatal hospitalizing steering assembly contact injury is assigned a benefit of 0.05 EFU (see Section 5.4).

Standards 203 and 204 were estimated to save 1347 lives (rounded to 1300 in Section 2.3); that is a contribution of 1347 EFU eliminated. They were estimated to enable 24,221 drivers to avoid steering assembly contact injuries resulting in hospitalization (rounded to 24,200 in Section 2.3); 22,874 of these cases are nonfatal (i.e. 24,221 minus 1347) and they make a contribution of 1144 EFU eliminated (i.e. 22,874 multiplied by 0.05). A total of 2491 EFU would have been eliminated by Standards 203 and 204 in 1978, if all passenger cars had been in compliance. Since the annual cost of Standards 203 and 204 is $104.6 million, they eliminate 23.8 EFU per million dollars of cost.

The confidence bounds for the number of EFU eliminated by Standards 203 and 204 are 1907 to 3074 (see Section 5.4). Thus, the confidence bounds for cost-effectiveness are 18.2 to 29.4 EFU eliminated per million dollars.

For comparison, Standard 214 - Side Door Strength - has been evaluated by NHTSA and found to be cost-effective [37]. It eliminates 5.3 EFU per million dollars (confidence bounds: 2.7 to 7.9).

2.5 Specific questions concerning the effectiveness of Standards 203 and 204

The preceding sections presented the evidence that Standards 203 and 204 are effective in preventing fatalities and serious injuries. But they did not address why the Standards are effective, nor, for that matter, why they are not more effective.

The "why" questions will be addressed here in the form of analyses of specific issues regarding the performance of post-Standard cars. Their actual performance in crashes will be compared to expectations based on design considerations and performance in controlled tests (see Sections 3.3, 3.4 and 3.5).

2.5.1 Displacement of the steering column into the passenger compartment

Perhaps the most serious shortcoming of the pre-Standard steering assembly was the displacement of the column into the passenger compartment. The pre-Standard column was rigidly linked to the car's frontal structure. In a severe frontal crash, the deformation of the frontal structure pushed the column rearwards, upwards or sideways into the passenger compartment at a high rate of speed. This phenomenon is known as column intrusion. Since, in frontal crashes, the vehicle structure is most commonly deformed rearward, the direction of column displacement is most often rearward. This is also the most hazardous form of column intrusion because the steering assembly is propelled directly towards the driver. (See Sections 3.3.2 and 3.5 and Figures 3-1 - 3-7.)

Column intrusion of 1 inch or more - rearward, upward or sideways - occurred in 3.5 percent of the pre-Standard frontal towaway crashes on the NCSS file. Yet this fairly small number of crashes produced 20 percent of the steering assembly contact injuries (fatal or requiring hospitalization) and 27 percent of the AIS $\geq$ 3 steering assembly contact injuries that resulted in death or hospitalization (see Section 3.2). (The NCSS investigators only observed the displacement of the steering wheel into the passenger compartment at final rest and, of course, could not measure dynamic displacement during the crash.)

A large portion of the steering assembly research and development was devoted to intrusion reduction (see Section 3.4). The problem was considered important enough to require a Federal Motor Vehicle Safety Standard of its own - Standard 204.

The compliance test for Standard 204 specifies that rearward column intrusion shall not exceed 5 inches at any time during a 30 mph frontal barrier crash. Manufacturers responded by installing steering assemblies with sections that telescope, buckle or articulate, so that the rearward deformation of the car's frontal structure is not translated into rearward intrusion of the steering wheel into the occupant compartment.

A small number of pre-Standard cars were subjected to the compliance test and failed it badly - the steering columns were displaced into driver's normal seating area. Since 1968, many post-Standard cars have been tested for compliance and there have been only 4 failures, which occurred in models accounting for well under 1 percent of the automobiles sold in the United States. No failures occurred after 1971 (see Section 6.1).

The performance of Standard 204 in actual highway accidents is nearly as good as the compliance test results. Post-Standard cars had a 68 percent lower incidence of steering column intrusion in NCSS frontal crashes than pre-Standard cars. The reduction is statistically significant. By contrast, the NCSS intrusion rates in frontal crashes for components other than the steering column were about the same for pre-Standard 204 and post-Standard cars. In other words, vehicle design changes other than Standard 204 did not have much effect, if any, on intrusion in frontal crashes. Thus, the large reduction in column intrusion is due, specifically, to the hardware installed in response to Standard 204.

Standard 204 resulted in a reduction of column intrusion in frontal crashes at all severity levels: the incidence of intrusion was reduced by 88 percent in crashes with Delta V 1-14 mph; the reduction in crashes with Delta V 15-29 mph was 62 percent; even when Delta V was 30 mph or more - crashes above the compliance test speed - intrusion was reduced by 39 percent.

The definition of "column intrusion" used above is any permanent displacement of the steering wheel into the passenger compartment - rearward, upward, downward or sideways - of one inch or more. Standard 204, however, only specifies limits on rearward intrusion. Engineers have expressed concern that the hardware installed in response to the Standard would not prevent upward and sideways intrusion, which could result in a safety hazard.

Analysis of Standard 204 compliance test films confirmed that upward intrusion was common in 30 mph barrier crashes, but was generally limited to a few inches. More substantial upward intrusion (up to 10 inches) occurred in a few small imported cars which use a series of universal joints in the steering shaft in order to meet Standard 204 [31].

The NCSS cases collected after March 1978 contain measurements of the primary direction of intrusion. The "primary" direction of intrusion (rearwards, upwards or sideways) is the axis which comes closest to the actual direction of displacement. They confirm the engineers' concern that Standard 204 is only effective against primary rearward intrusion: 4.6 percent of the pre-Standard cars displayed rearward intrusion, versus 0.9 percent of the post-Standard cars (a significant 81 percent reduction of rearward intrusion). On the other hand, in 0.5 percent of the pre-Standard cars there was measurable intrusion in a primarily upward, downward or sideways direction, versus 0.8 percent of the post-Standard cars (a non-significant 68 percent increase of vertical and sideways intrusion.)

Vertical and sideways intrusion are less serious than rearward intrusion as direct sources of injury. Table 2-7 shows that rearward column intrusion occurred in 18 percent of the pre-Standard cars in which the driver suffered fatal or hospitalizing steering assembly contact injury, but vertical or sideways intrusion was only associated with 3 percent of the injuries. Standard 204 reduced the association of rearward intrusion with serious injury to just 6 percent in post-Standard cars. Standard 204 did not reduce vertical and sideways intrusion, which are associated with only 4 percent of the injuries in post-Standard cars.

TABLE 2-7

COLUMN INTRUSION INVOLVEMENT IN SERIOUS INJURIES

Percent of Serious Steering Contact Injuries with:	Pre-Standard Cars	Post-Standard Cars
Rearward column intrusion	18	6
Vertical or sideways intrusion	3	4
Catastrophic vehicle damage	3	6
No intrusion (i.e. less than 1 inch)	76	84

Since column intrusion is associated with 20 percent of the serious injuries caused by steering assembly contact and Standard 204 reduced intrusion by two-thirds, this Standard alone may be credited with 1/3 to 1/2 of the total serious injury reduction due to Standards 203 and 204, combined. Since intrusion is associated with an even higher percentage of the fatalities and AIS $\geq$ 3 injuries, Standard 204 may alone be responsible for an even higher fraction of the overall fatality reduction.

2.5.2 Effectiveness of alternative energy-absorbing devices

There are 6 major types of energy-absorbing steering assemblies in use. Five of them contain an energy absorbing device (EAD) in the steering column assembly between the instrument panel and the firewall. Although the design of the EAD varies, it serves the same functional purpose. They are the mesh, ball, slotted, grooved and slotted/mandrel columns. The sixth type contains a collapsible canister just below the steering wheel hub. (See Section 3.4.3 and Figures 3-14 - 3-21.)

Although Standard 203 only tests performance under nearly axial load, safety researchers devoted considerable effort to developing a steering assembly that would also perform well under increased nonaxial load. The steering wheel canister design was a product of this effort (see Section 3.5).

Two British studies based on a relatively small sample of accident data have suggested the wheel canister is substantially more effective than the other types, because of its superior performance under a wide variety of nonaxial loading conditions (see Section 6.2) [29], [30].

The National Crash Severity Study, which contained a much larger sample of accident cases, did not exhibit any statistically significant differences between the principal designs of energy absorbing steering systems in regard to their observed effectiveness in reducing serious injuries (deaths and hospitalizations) due to steering assembly contact. Table 2-8 shows that there was virtually no difference in the effectiveness of the 4 most common energy absorbing column types: the mesh type was observed to reduce serious injury by 27 percent; the ball type, by 36 percent; the slotted and grooved columns, by 39 percent each.

TABLE 2-8

REDUCTION OF SERIOUS STEERING ASSEMBLY CONTACT INJURY BY ENERGY-ABSORBING DEVICE TYPE

EAD Type	N of NCSS Cases	% with Serious Injury	Injury Reduction (%)
None	3560	3.23	-
Mesh	4542	2.36	27
Ball	13,511	2.06	36
Slotted	4311	1.97	39
Grooved	3528	1.98	39
Slotted/mandrel	1355	1.55	52
Wheel canister	844	2.49	23

The slotted/mandrel type was observed to reduce injury by 52 percent; this estimate is based on a smaller sample than the preceding types and is not significantly higher than any of them.

The wheel canister had the lowest observed effectiveness of any type: 23 percent. But the estimate is based on only 844 NCSS cases and it is not significantly lower than the other types. The NCSS sample of wheel canister cases is, on the other hand, substantially larger than the sample used in the two British studies. The NCSS results refute the conclusion of those studies that the wheel canister type is "highly effective" relative to the column EAD designs.

2.5.3 Body regions injured by contact with the steering assembly

Some insight about why Standards 203 and 204 have been effective can be gained by comparing the extent to which they reduce injuries to the different body regions. Each hardware change made in response to Standards 203 and 204 is intended to alleviate specific injury mechanisms which create risk of injury to specific body regions. (See Sections 3.3.2, 3.4.3 and 3.5 and Figures 3-8 - 3-12.) Different levels of effectiveness, for various body regions, might indicate the relative success of various hardware changes.

Prior to discussing the effectiveness of Standards 203 and 204 by body region, however, it is appropriate to review the problem: the distribution of the injuries by body region.

Table 2-9 shows the distribution, by body region, of steering assembly contact injuries that resulted in fatality or hospitalization. In the right column, it shows the distribution of the most serious injuries within this group: the ones with AIS $\geq$ 3.

TABLE 2-9

BODY REGION DISTRIBUTION OF STEERING ASSEMBLY CONTACT INJURIES

Body Region	Percent of Drivers with Injury Resulting in: Fatality or Hospitalization	Fat/Hosp with AIS $\geq$ 3
Chest/shoulder	41	52
Head/neck	26	9
Abdomen/pelvis	20	28
Arm/leg	13	11

The chest was the body region most frequently injured due to steering assembly contact: 41 percent of the injuries resulting in death or hospitalization were chest injuries; 52 percent of the most serious injuries (AIS $\geq$ 3 and resulting in death or hospitalization) were chest injuries.

The head and neck was the next most common body region injured by the steering assembly, but the injuries were less serious. The head and neck accounted for 26 percent of the injuries requiring hospitalization, but only 9 percent of those with AIS $\geq$ 3.

Abdominal and pelvic injuries, on the other hand, tended to be more serious than average: 20 percent of the injuries requiring hospitalization and 28 percent of those with AIS $\geq$ 3 were in that body region.

The arms and legs were the least common location of injuries due to steering assembly contact.

What are the mechanisms that produce injuries to various body regions? How might they be alleviated by Standards 203 and 204?

Chest injuries in pre-Standard cars were typically blunt trauma, resulting from large, concentrated loads of the narrow hub of the rigid steering column on the driver's thorax. Chest injury was aggravated by rearward column intrusion. Bending away or breaking of the steering wheel rim and spokes would result in concentration of the load on the hub and would aggravate chest injury. Standards

203 and 204 might be expected to reduce chest injury because the energy absorbing device limits the load on the chest, because intrusion is reduced and because the improved steering wheel (stronger spokes and hub padding) prevents concentration of loads.

Abdominal injuries are of similar etiology to chest injuries, except that the abdomen cannot tolerate force levels as high as the chest. Abdominal injury is more likely to result from contact with the lower rim of the steering wheel than from the hub. Piercing injury may result from broken spokes. Since column intrusion in pre-Standard cars was largely rearward and upward, it created less risk of abdominal injury than chest or head trauma. Standards 203 and 204 might be expected to reduce abdominal injury because of the energy absorbing device (but less effectively than for chest injuries) and because of strengthened spokes and a smaller-diameter, more energy-absorbing steering wheel rim.

Most head, facial, neck and arm injuries do not involve loads on the steering assembly large enough to collapse the energy absorbing device. Standards 203 and 204 could be expected to reduce these injuries largely due to the voluntary steering wheel improvements, such as removal of horn rings and metal trim, hub padding, and reduction of the steering wheel diameter. Reduction of column intrusion, together with a steering column angle that has become more nearly horizontal over the years, may also have reduced the risk of the steering wheel being thrust towards the driver's head and neck.

Although the various body regions are affected by different injury mechanisms, there were no statistically significant differences in the extent to which Standards 203 and 204 reduce injury to specific body regions. Table 2-10 shows the reduction, by body region, of steering assembly contact injuries resulting in fatality or hospitalization. Chest injuries declined by 28 percent due to Standards 203 and 204. Head and neck injuries experienced the largest reduction (45 percent) and abdominal injuries, the smallest (22 percent). Arm and leg injuries dropped by 42 percent. Because of the relatively small samples of injuries for specific body regions, the differences between the reductions are not significant.

TABLE 2-10
REDUCTION OF SERIOUS STEERING ASSEMBLY CONTACT INJURY
BY BODY REGION

Body Region	Injury Reduction for Standards 203 and 204 (%)
Chest/shoulder	28
Head/neck	45
Abdomen/pelvis	22
Arms/legs	42

What are the implications of this approximate equality of effectiveness, by body region?

(1) Head, neck and arm injuries generally do not involve loads on the steering column sufficient to compress the energy-absorbing device. The substantial reduction of these injuries in post-Standard cars, therefore, must to a large extent be due to improvements made voluntarily by the manufacturers: removal of horn rings and metal trim; padded hubs; stronger spokes; smaller, more energy-absorbing steering wheels; more nearly horizontal column alignment.

(2) Serious chest and abdominal injuries usually involve substantial driver loads on the steering column. The substantial reduction of these injuries could not have occurred unless the energy absorbing devices had successfully compressed and protected the drivers in many crashes: intrusion reduction and steering wheel improvements, alone, would not likely have caused such a large injury reduction. On the other hand, the fact that the chest injury reduction is not substantially higher than the head injury reduction suggests that the energy absorbing devices, which were primarily designed to prevent torso injuries, have not been foolproof (see Section 6.3.2).

Since head, neck and arm injuries account for over 30 percent of the steering assembly contact injuries requiring hospitalization and because these injuries were reduced largely due to voluntary steering wheel improvements, it would appear that the voluntary improvements account for 1/4 to 1/3 of the overall injury reduction attributed to Standards 203 and 204 (but a much smaller percentage of the fatality reduction, since these injuries are rarely fatal). The voluntary improvements were, however, not uniformly extended to the vehicle fleet. Some steering wheels were not significantly improved and continued to pose a hazard to the driver (see Figure 3-37).

2.5.4 Effect of Standards 203 and 204 on injuries due to contacts other than the steering assembly

A potential drawback of the compressible, non-intruding post-Standard 203 and 204 steering assembly was the concern that it might allow the driver's body to move forward to the point where the head or legs contact the windshield or instrument panel, with resultant injuries [33], [65].

The NCSS data do not support a conclusion that injuries due to other components increased as a consequence of Standards 203 and 204. An analysis was performed on drivers who contacted the steering assembly (with or without injury) and suffered serious injury from components other than the steering assembly (see Section 6.4).

The risk of a pre-Standard car driver contacting the steering assembly and sustaining a serious injury from another component was 1.43 percent in frontal towaway crashes. The comparable risk in post-Standard cars was 1.30 percent. This is a nonsignificant 9 percent reduction in the risk of secondary serious injury accompanying steering assembly contact.

The NCSS data, then, support the conclusion that Standards 203 and 204 did not have negative side effects (injuries from other sources). This conclusion is consistent with engineering intuition: in the vast majority of crashes, the pre-Standard column does not intrude more than a few inches and the post-Standard column does not compress more than a few inches. Thus, the steering wheel movement relative to the remainder of the passenger compartment is rarely large enough to significantly affect other contact points.

This NCSS analysis must be viewed with an extra degree of caution, however, because of the large proportion of missing data on minor injury contact points and the absence of information on noninjury contact points. Also, changes in the design of other components (windshield, dashboard) during the 1960's may have affected injury risk from those components.

2.5.5 Compressibility of the energy-absorbing devices

The steering wheel and column energy absorbing devices (EAD) installed in response to Standard 203 were designed to compress or telescope when the driver contacted the steering wheel (see Sections 3.4 and 3.5). They were to compress at a controlled rate, absorbing the load of the driver's torso at a nondangerous force-deflection level.

In-depth accident investigation showed that when the EAD compressed properly it was highly effective in reducing injury severity (see Figures 3-26 - 3-32). It also revealed that the EAD often did not compress properly (see Figures 3-33 and 3-34). The tendency of the EAD to bind rather than telescope has been one of the most controversial issues surrounding Standard 203. Some of the questions regarding the EAD are:

- How serious is the problem?
- What causes binding of the EAD?
- Are some EAD designs more susceptible to binding than others?
- What is the best way to measure compression due to occupant loading?
- How does EAD performance in accidents relate to the compliance test for Standard 203?

The compliance test for Standard 203 specifies that the force in the steering column must not exceed 2500 pounds during contact with an 80 pound torso block travelling at 15 mph (22 feet per second) [22], [23]. In fact, the energy absorbing columns installed in response to Standard 203 had a maximum force deflection characteristic of 1800 pounds [65]. At that force level, it would take 4 inches of EAD compression to stop the 80 pound torso moving 15 mph.

The average EAD compression in 15 mph highway accidents, however, is far less than 4 inches. Table 2-11 shows the distribution of EAD compression (or shear capsule separation) in frontal crashes in which the driver contacted the steering assembly and in which the vehicle damage extended to zone 3 or further. These are frontal crashes in which the Delta V was usually at least 15 mph and often much higher. Multidisciplinary accident investigation data were used because NCSS does not contain information on EAD compression. Only 17 percent of the columns had 3 inches or more compression, whereas 55 percent had less than 1 inch. (The "shear capsule" is a component of certain energy absorbing steering systems and its amount of separation during a crash is a measure of EAD compression due to occupant load - see Section 3.4.3 and 6.5 and subsequent discussion in this Section.)

TABLE 2-11

EAD COMPRESSION IN FRONTAL CRASHES WITH DAMAGE EXTENT ZONE 3-9 AND IN WHICH DRIVER CONTACTED STEERING ASSEMBLY

EAD Type	How Compression Measured	Percent of Cases with Inches of Compression:		
		0 - 0.9	1 - 2.9	3+
Mesh	Shear capsule sep.	44	36	20
Ball	Shear capsule sep.	51	27	22
Slotted	Shear capsule sep.	68	23	9
Grooved	EAD compression	72	19	9
Slotted/mandrel	Shear capsule sep.	46	42	12
Wheel canister	EAD compression	61	22	17
ALL TYPES		55	28	17

Table 2-11, however, exaggerates the problem of EAD noncompression. Even in relatively severe crashes where the driver contacts the steering assembly, the load on the column is often too low to substantially compress the EAD. This is because a large portion of the torso's kinetic energy is dissipated during the vehicle's ridedown phase of the collision or through leg contact with the instrument panel or other contact points (see Section 6.5.1 and [65]).

The problem of noncompression is better gauged by examining only those crashes in which the driver exerted a heavy load on the steering column. Evidence of heavy loads includes

- severe deformation or breakage of the steering wheel or spokes, <u>or</u>
- at least 3 inches of shear capsule separation (or EAD compression in columns without shear capsules).

In this evaluation, the EAD is said to have <u>failed</u> under heavy load if there was severe deformation or breakage of the wheel or spokes and less than one inch of compression. On the other hand, 3 inches or more of shear capsule separation indicate <u>successful</u> compression of the EAD (regardless of the condition of the wheel and spokes). Only in 36 percent of the crashes in Table 2-11 did the driver exert a load on the column severe enough to produce a success or failure under these definitions.

Table 2-12 shows the ratio of "successes" to "failures" of EAD compression under heavy driver loading. For all types of energy absorbing devices combined, there were 47 successes for every 53 failures - for all practical purposes a ratio of 1 to 1. Table 2-12 suggests that

(1) Failure of the column to compress under heavy driver load is a serious problem.

(2) It is not as serious as suggested by previous studies which did not take into account the high incidence of noncompression due to lack of load [28], [29], [30], [45].

TABLE 2-12

SUCCESSES AND FAILURES OF EAD COMPRESSION UNDER HEAVY DRIVER LOADS

EAD Type	Ratio of Successes* to Failures**	N of Successes and Failures
Mesh	50:50	101
Ball	57:43	221
Slotted	31:69	96
Grooved	32:68	37
Slotted/Mandrel	43:57	7
Wheel canister	38:62	8
ALL TYPES	47:53	470

* 3 inches or more capsule separation (or EAD compression)

** Severely deformed or broken wheel or spokes with less than 1 inch compression

The principal cause of failures to compress is nonaxial loading of the column. In other words, the direction of the force exerted by the driver on the column is not parallel to the alignment of the column. Many factors, however, contribute to nonaxial loading:

Frontal damage to the vehicle may cause deformation of the bottom of the column. As a result, the driver load through the top part of the column is nonaxial relative to the lower part and the EAD locks up instead of compressing [30].

The driver's movement in frontal crashes is usually horizontal whereas the column is angled downwards. As a result, the driver's momentum is not collinear with the column [28], [30]. Laboratory testing clearly demonstrated how this vertical angle adversely affects EAD compression [15].

Upward intrusion and rotation of the column increases the vertical angle between the driver's momentum and the column alignment (see Figure 3-33). Even small amounts of upward intrusion may significantly reduce EAD performance [28].

The unfavorable alignment of the steering wheel spokes at the time of a crash may result initially in the driver's load concentrating on the steering wheel rather than the column and, subsequently, in a nonaxial column load because wheel deformation has altered the direction of driver motion. The effect of unfavorable spoke alignment was demonstrated by laboratory testing [15] and in-depth investigation (Figure 3-36). Conversely, a steering wheel with three strong spokes reduces the likelihood of unfavorable alignment [65]. Three-spoke wheels were voluntarily introduced in some post-Standard cars, but not in all of them.

Nonaxial loads or vehicle damage can cause locking up of telescoping column components besides the EAD - e.g., the steering shaft or the shift tube - and result in column noncompression.

When the vehicle is involved in an oblique frontal crash, the direction of driver movement tends to be at a lateral angle to the column alignment. Oblique crashes may also cause sideways intrusion or rotation of the column (see Figure

3-34). Both phenomena produce nonaxial column loading and reduce column compression. The deterioration of EAD performance due to lateral forces, however, is not that large: laboratory testing showed that column compression was about the same for a body block contacting the column at a 15 degree lateral angle as it was when the block moved in line with the column [15]. Table 2-13 shows that, in highway accidents, crash forces ranging from 15 to 45 degrees away from longitudinal (Principal Direction of Force 11:00 or 1:00) caused a moderate reduction of column performance. The ratio of "successful" EAD compression to "failure" under heavy driver loading was 39:61 in the oblique crashes, as compared to 50:50 in the direct frontal crashes (force within 15 degrees of longitudinal-12:00 Principal Direction of Force).

TABLE 2-13

SUCCESSES AND FAILURES OF EAD COMPRESSION
UNDER HEAVY DRIVER LOADS, BY PDOF

Principal Direction of Force	Ratio of Successes* to Failures**
12:00	50:50
11:00 or 1:00	39:61

* 3 inches or more of shear capsule separation (or EAD compression)
** Severely deformed or broken wheel or spokes with less than 1 inch compression

There appear to be moderate <u>differences between EAD designs</u> in regard to compressibility. Tables 2-11 and 2-12 both suggest that the ball type column performs slightly better than the other designs. It is the only column with 3 inches of shear capsule separation in more than 20 percent of severe frontal crashes and it is the only design for which EAD compression "successes" under heavy driver load exceed "failures" (by a 57:43 margin). The mesh and slotted/mandrel column performance was slightly inferior to the ball type.

The slotted and grooved columns appear to have the lowest average compression and the lowest ratio of successes to failures. These 2 designs, however, were just as effective in preventing injuries as the ball type (see Table 2-8 based on NCSS data). It is possible that both of these columns were installed in conjunction with a steering wheel designed to deform and absorb a substantial share of the driver's energy (thereby increasing the number of "failures" according to the criterion of Table 2-12, yet protecting the driver from injury). It is also possible that compression of the grooved columns was sometimes underestimated in the multidisciplinary accident investigation data (see Section 6.5.2).

The performance of the wheel canister EAD was nearly the same as the average of the other 5 types. The wheel canister was also not found to be more effective than any of the other types when it came to preventing injuries (see Table 2-8). Thus, the results of this evaluation do not support the claims of earlier studies [29], [30] that the wheel canister is substantially less prone to binding and substantially more effective.

The best measurement of EAD compression due to driver loading in mesh, ball, slotted and slotted/mandrel columns is the shear capsule separation. In these column types, the shear capsule is a device which is designed to separate when the driver compresses the column downwards (see Section 3.4.2). The EAD itself, on the other hand, is designed to compress as a result of vehicle damage as well as driver loading - it plays a role in the compliance test for Standard 204 as well as 203. EAD compression, then, need not be due to driver loading alone. In frontal accidents where the driver contacted the steering assembly, 16 percent of the columns had 3 inches of EAD compression but only 10 percent had 3 inches of shear capsule separation, so it is clear that the former measurement would considerably exaggerate compression actually due to occupant loading.

It has also been suggested that even shear capsule separation may be due to vehicle damage [30]. The accident data, however, suggest this is a rare phenomenon. In frontal crashes where the driver did not contact the steering assembly, only 1 percent of the columns had an inch of shear capsule separation and none had 3 inches. By contrast, 3 percent had 1 inch of EAD compression and 1 percent had 3 inches. (See Section 6.5.2.) Shear capsule separation is, at worst, a slight exaggeration of compression due to driver loading.

The grooved column and the wheel canister are not equipped with shear capsules and the EAD is not designed to compress due to vehicle damage. The EAD compression in these cars may be attributed to driver loading.

Finally, how does EAD performance in accidents relate to the compliance test for Standard 203? Compliance is determined by a laboratory test in which a body block moves directly foward to strike an undamaged steering assembly mounted at the manufacturer's installation angle. The resultant forces on the column are relatively close to axial. In highway accidents, the steering assembly is often partially damaged before the driver contacts it. It is then struck by the driver with a force that is often strongly nonaxial with respect to the column. EAD designs which are susceptible to binding under nonaxial loading conditions may readily pass the Standard 203 compliance test but fail to compress under heavy driver loading in many highway accidents. All of the major EAD designs currently on the highway appear to meet this description.

There are many causes of nonaxial column loading. The most important ones appear to be

- Deformation of the lower column due to vehicle damage
- Vertical angle between the driver's movement and the column alignment
- Upward column intrusion and rotation
- Unfavorable steering wheel spoke alignment
- Oblique frontal crash forces

An improved compliance test for Standard 203 – a test that would detect tendencies of a column to bind in highway accidents – may have to simulate many or all of the above nonaxial force phenomena, especially the effect of initial vehicle damage. Simply extending the current test to include one oblique impact with an undamaged column may not be sufficient: one of the current post-Standard columns has passed such a test [15] but often binds in highway accidents.

The problem of unfavorable steering wheel spoke alignment is of special concern. It is possible that the three-spoke steering wheels voluntarily installed in some makes and models may have remedied the problem at relatively low cost. But Standard 203 does not currently specify performance requirements that would motivate installation of three-spoke wheels, or an equivalent improvement, on a fleet-wide basis.

Finally, the current columns, despite their shortcomings, do compress as designed in many crashes. This evaluation has attempted to provide objective definitions of "successful" and "unsuccessful" compression and has found the ratio of the two to be close to 50:50. The overall effectiveness of Standards 203 and 204 is not attributable to intrusion reduction and steering wheel improvements alone and must, to a large extent, be due to the successful compression of the EAD by the driver in many crashes (see Sections 2.5.1 and 2.5.3).

2.5.6 Role of the principal direction of force

The principal direction of force (PDOF) experienced by the crash-involved vehicle influences the driver's kinematics. The driver's movement generally parallels the force vector. In crashes where the principal direction of force is within 15 degrees of frontal (12:00 PDOF, in the terminology of accident investigators [11],) many drivers will move straight ahead into the steering wheel. In more oblique frontal crashes, many drivers may avoid contacting the wheel or strike it lightly. If they do make a firm contact, there is a nonaxial force component which tends to reduce the performance of the energy absorbing device (see Table 2-13). Lower steering assembly contact injury risk and lower effectiveness for Standards 203 and 204 would be expected in oblique frontal crashes.

Table 2-14 shows that, indeed, the risk of serious injury due to steering assembly contact in pre-Standard cars was nearly 3 times higher when the PDOF was within 15 degrees of longitudinal than in oblique frontal crashes. Even though only 56 percent of frontal towaway crashes were directly frontal (12:00 PDOF), they accounted for 77 percent of the serious steering assembly contact injuries in pre-Standard cars (see Section 3.3.3).

TABLE 2-14

EFFECTIVENESS OF STANDARDS 203 AND 204 BY

PRINCIPAL DIRECTION OF FORCE

PDOF	Percent with Serious Steering Assembly Contact		Injury
	Pre-Standard	Post-Standard	Reduction (%)
12:00 (with 15° of frontal)	4.37	2.68	39
10:00*, 11:00,** 1:00,** or 2:00* (oblique frontal)	1.59	1.40	12

*crashes with frontal damage only **includes side damage

The effectiveness of Standards 203 and 204 was 39 percent in crashes where the direction of force was within 15 degrees of frontal. The effectiveness was just 12 percent in the oblique frontal crashes. The difference of effectiveness, however, was not statistically significant (see Section 6.6).

Since the oblique frontal crashes account for a relatively small proportion of the serious injuries due to steering assembly contact, the potential benefits of upgrading the performance of steering columns in these crashes is somewhat limited (unless there are corresponding improvements in direct frontal crashes).

2.5.7 Role of the crash velocity change (Delta V)

Delta V, the magnitude of the vector denoting a crash-involved vehicle's velocity change during the impact, is a measure of collision severity experienced by that vehicle.

The Delta V distributions of vehicles whose drivers suffered serious steering assembly contact injuries is about the same as the distribution for other serious injuries in frontal crashes (see Section 3.3.4).

The equipment installed in response to Standards 203 and 204 is designed to provide some protection at many levels of Delta V: the steering wheel improvements such as hub padding and removal of horn rings should be especially effective at low speeds; at medium speeds, driver load on the steering assembly becomes large enough to compress the energy absorbing device; at high speeds, Standard 204 mitigates the danger of column intrusion.

The NCSS data do not exhibit any significant trend of Standard 203/204 effectivenss as a function of Delta V. Table 2-15 shows that the observed effectiveness was 34 percent in crashes with Delta V less than 10 mph; 32 percent in crashes with Delta V of 10-19 mph; 44 percent when Delta V was 20-29 mph; and 32 percent in crashes with a Delta V of 30 mph or more.

TABLE 2-15

EFFECTIVENESS OF STANDARDS 203 AND 204 BY DELTA V

Delta V	Percent with Serious Steering Assembly Contact Injury		Injury
(mph)	Pre-Standard	Post-Standard	Reduction (%)
1 - 9	0.54	0.35	34
10 - 19	2.67	1.83	32
20 - 29	13.39	7.50	44
30+	27.8	18.8	32

Standards 203 and 204 are effective over a wide range of crash severity. It may be speculated that each of the major devices installed in response to the

Standards - improved steering wheels, energy absorbing devices and intrusion-reducing devices - have been effective within the speed range for which they were designed and, perhaps, also somewhat beyond their range.

2.6 Conclusions

The problem

- Standards 203 and 204 addressed themselves to specific, quantifiable motor vehicle safety problems of major importance.

Overall effectiveness

- The equipment installed or modified in response to Standards 203 and 204 has reduced driver fatalities in frontal crashes.
- It has reduced serious nonfatal injuries to drivers in frontal crashes.
- Standards 203 and 204 are cost-effective.

Why have Standards 203 and 204 been effective?

- Standard 204 has been highly effective in reducing rearward steering column displacement. This factor accounts for about 1/3 to 1/2 of the total injury reduction and an even higher fraction of the total fatality reduction for Standards 203 and 204, combined.

- The energy absorbing devices installed in response to Standard 203 are successfully compressed (3 inches or more) in about half the crashes in which they are heavily impacted by the driver. This factor accounts for about 1/4 to 1/3 of the total injury reduction and an even larger fraction of the total fatality reduction for Standards 203 and 204, combined.

- The improvements to steering wheels that manufacturers voluntarily made at about the time that Standards 203 and 204 took effect - hub padding, removal of horn rings, stronger rims and spokes - have substantially reduced head and arm injuries. They have also contributed to the effective operation of the energy absorbing devices. They account for about 1/3 of the overall injury reduction (but a much smaller fraction of the fatality reduction) for Standards 203 and 204, combined.

° The significant steering assembly contact injury reduction due to Standards 203 and 204 and the successful or partially successful performance as intended, in crashes, by each of the major equipment modifications is proof that the compliance test conditons are relevant to some aspect of actual highway performance.

Shortcomings of Standards 203 and 204

° The principal shortcoming of Standards 203 and 204 has been the failure of the energy absorbing devices to compress in about half the crashes in which they are heavily impacted by drivers.

° Energy absorbing devices and other steering assembly components tend to bind rather than compress when they are exposed to nonaxial loads.

° Nonaxial loads may be a consequence of inital vehicle damage, unfavorable driver kinematics, upward steering column displacement, unfavorable steering wheel spoke alignment and oblique frontal crash forces.

° Standard 204 has not reduced the incidence of steering column displacement in a primarily upwards or sideways direction.

- The improvements to the spokes, rim and face of steering wheels were largely voluntary. Since they are not required for compliance, they have not been uniformly applied to the vehicle fleet.

Side effects of Standards 203 and 204

- The Standards do not appear to have had negative side effects: there was no increase in serious injury from contact points other than the steering assembly.

Comparison of alternative energy absorbing devices

- The six major designs of energy absorbing devices are about equally effective in reducing serious injuries.

- The various devices did not differ substantially in their tendency to bind under driver load.

- They all cost approximately the same.

- A British study concluded that the steering wheel canister is more effective and more easily compressible than the energy absorbing columns. This evaluation does not support their conclusion.

Potential for improving Standards 203 and 204

- There may be potential benefits in extending the Standard 203 requirements, which currently simulate energy absorbing device performance only under nearly axial column load, to include tests that simulate nonaxial loading situations.

- For substantially increased benefits, it may be necessary to realistically simulate many of the conditions that lead to nonaxial loading, such as initial vehicle damage, unfavorable driver kinematics, upward steering column displacement, unfavorable steering wheel spoke alignment and oblique frontal crash forces.

- Upward column displacement, even in small amounts, can aggravate column binding. In larger amounts, it can magnify head injury risk. There may be potential benefits in modifying the requirements of Standards 203 and 204 to reduce both types of hazard associated with upward column displacement.

- The voluntary steering wheel improvements have not been uniformly implemented. There may be potential benefits in adding performance requirements to Standard 203 that would result in the use of crashworthy steering wheels in the entire vehicle fleet.

CHAPTER 3

A REVIEW OF THE STEERING ASSEMBLY CONTACT INJURY PROBLEM AND STANDARDS 203 AND 204

There are more fatalities and serious injuries to passenger car drivers than to occupants of any other seat position. More drivers are killed or seriously injured in frontal impacts than in any other type of crash. The steering assembly is the most common injury-producing contact point for drivers in frontal crashes. These considerations make steering assembly contact injury a prime target for the motor vehicle safety program.

The first section of this chapter is a statistical assessment of the dimensions of the problem. The remaining sections analyze particular aspects of the problem in greater depth and describe the remedies implemented in response to Standards 203 and 204.

3.1 Incidence of steering assembly contact injury

3.1.1 Results from earlier studies

The Automotive Crash Injury Research (ACIR) program, which was initiated in 1951, allowed a statistical evaluation of injury causation. In 1956, John Moore of the Cornell Aeronautical Laboratory relied on ACIR data when he testified before a Congressional committee about the relative importance of the steering assembly as a cause of driver injury [28]. By 1962, the ACIR file contained 19,300 injured occupants of passenger cars built after 1955. Schwimmer and Wolf reported that the steering assembly ranked second only to ejection as a source of fatalities and dangerous injuries - even though the file was not limited to drivers or frontal crashes [71]. The steering assembly was the source of 133 out of 759 fatalities: it accounted for 17 percent of the passenger car occupant fatalities on ACIR, which would have corresponded to a nationwide total of over 4,000 deaths per year. Steering contact was the predominant source of non-minor injury, accounting for 21 percent of the dangerous non-fatal injuries and 22 percent of the non-dangerous non-minor passenger car occupant injuries.

Huelke and Gikas analyzed 78 in-depth investigations of passenger car driver fatalities that occurred in the Ann Arbor area during 1961-65 [35]. They determined that 24 of the 78 driver deaths, or 31 percent, were due to steering assembly contact. The steering assembly was the number one cause of driver deaths, even outranking ejection.

Nahum, Siegel and Brooks reported that 48 percent of the non-minor driver injuries in frontal crashes resulted from steering assembly contact [56]. The statistic is based on 178 passenger cars of model years 1960-66 covered in Los Angeles area multidisciplinary accident investigations.

Note that Schwimmer and Wolf's statistics apply to all types of occupants in all types of crashes; Huelke and Gikas to drivers in all types of crashes; and Nahum's to drivers in frontal crashes. All 3 studies, then, suggest that close to half of the driver injuries and fatalities in frontal crashes, prior to Standards 203 and 204, were due to steering assembly contact.

3.1.2 Results from the National Crash Severity Study

The National Crash Severity Study (NCSS) is primarily a file of towaway crashes of passenger cars. The file is described in detail in Section 5.2.1. In the pre-Standard 203 and 204 cars on NCSS, the steering assembly was, by far, the most common source of injury to drivers involved in frontal towaway impacts. Table 3-1 shows that the steering assembly was the most severe injury source for 50 percent of the drivers who were killed or hospitalized. The second most frequent source, the instrument panel and its appurtenances, caused the most severe injury of just 15 percent of the drivers. The NCSS results agree closely with the earlier studies.

It is possible to sustain 2 or more crash injuries, each of which, by itself, would have been sufficient to cause death or hospitalization. In this study, drivers are assumed to have 2 fatal or hospitalizing injuries if their 2nd most severe injury

- has the same AIS as the most severe injury, <u>or</u>
- is rated AIS 3 or greater.

TABLE 3-1

SOURCE OF MOST SEVERE FATAL OR
HOSPITALIZING INJURY, DRIVERS OF
PRE-STANDARD CARS IN FRONTAL CRASHES, NCSS
(Known Injury Source)

Source	N of Drivers	%
Steering assembly	108	50
Instrument panel, hardware on the panel, A/C	31	15
Windshield	28	13
Side interior surface, objects attached to side, A-pillar	14	7
Header, sun visor, rearview mirror	12	6
Non-contact injury (due to impact force)	11	5
Objects exterior to passenger compartment	7	3
Other known contact source	3	1

Table 3-2 classifies the pre-Standard car driver fatalities and hospitalizations, in frontal crashes, according to the 2 most severe injuries. A total of 58 percent of the drivers suffered injury from steering assembly contact which, by itself, would have resulted in death or hospitalization: 46 percent sustained serious injury from the steering column alone and 12 percent sustained serious injuries from 2 sources, one of which was the steering assembly. Forty-two percent of the drivers who were killed or hospitalized did not suffer serious injury resulting from steering contact.

Table 3-2 should be interpreted as follows: suppose the effectiveness of Standards 203 and 204 is ε and the number of drivers killed or hospitalized in frontal crashes, in the absence of the Standards, is N. Then, there would be a total of $.58\,\varepsilon\,N$ fewer drivers with serious injuries due to steering assembly contact; $.46\varepsilon N$ drivers would not be killed or hospitalized at all, as a result of the Standards. An additional $.12\,\varepsilon\,N$ would benefit by avoiding serious steering assembly contact injury, although they would still have injuries from other sources that, by themselves, would require hospitalization or even cause a fatality.

The actual number of deaths and serious injuries due to steering assembly contact - the absolute dimensions of "the problem" - is estimated in Table 3-3. This table shows the number of deaths and serious injuries that <u>would have</u> occurred in 1978 if none of the passenger cars on the road complied with Standards 203 and 204, i.e. those that actually occurred plus those that were prevented by the Standards. The formulas used to obtain the estimates are presented at the very end of Sections 5.2.4. and 5.3.2. (The derivation of the formulas is postponed to those sections because the formulas are based on procedures developed there.)

TABLE 3-2

DISTRIBUTION OF FATAL OR HOSPITALIZING INJURIES BY CONTACT SOURCES, DRIVERS OF PRE-STANDARD 203 AND 204 CARS IN FRONTAL CRASHES, NCSS

Source of Injuries	N of Drivers	Percentage of Crash-Involved Drivers	Percentage of Injured Drivers	Percentage of Injured Drivers with Known Contact Points
Steering assembly only	99	2.5	30.3	46.3
Steering assembly and other contacts	25	0.6	7.6	11.7
Other known contact points	90	2.3	27.5	42.0
Unknown contact points	113	2.9	34.6	-
None - driver not killed or hospitalized	3624	91.7	-	-

Table 3-3 shows that, in the absence of Standards 203 and 204, there would have been approximately 11,000 drivers killed and 109,000 hospitalized in crashes with frontal damage or direction of force. Based on the contact point distributions of Table 3-2, there would have been about 50,000 fatalities and serious injuries due to steering contact alone plus 13,000 drivers killed or seriously injured by the steering assembly and another source. Table 3-3 shows that 26 percent of all passenger car occupant fatalities and serious injuries and 39 percent of driver fatalities and serious injuries were due, entirely or partially, to steering assembly contact.

TABLE 3-3

NUMBER OF FATALITIES AND HOSPITALIZING INJURIES THAT WOULD HAVE OCCURRED IN 1978 IF STANDARDS 203 AND 204 HAD NOT BEEN PROMULGATED

	Fatalities	Fatalities and Hospitalizing Injuries
All passenger car crashes	29,600	240,000
Passenger car drivers	19,600	160,000
Drivers in frontal crashes	10,900	108,800
Serious injury due to:		
Steering assembly only	unk.	50,400
Steering and other contacts	unk.	12,700
Other contacts only	unk.	45,700

Reliable contact point distributions for fatally injured drivers were not available from NCSS. If the contact point distribution were the same as for the serious injuries there would have been about 5,000 fatalities (46% of 10,900) due to steering assembly contact only. If frontal fatalities are more likely to involve multiple injury or ejection than the non-fatal serious injuries – a reasonable assumption – the number of fatalities due primarily to steering contact would probably have been about 3 – 4,000.

The contact point distribution of the driver's most severe injury is classified by AIS level [1] in Table 3-4. The table includes persons with known overall AIS plus those assigned to AIS categories on the basis of their treatment and police injury code (see Section 5.2.1.).

TABLE 3-4

SOURCE OF MOST SEVERE INJURY CLASSIFIED BY AIS LEVEL
DRIVERS OF PRE-STANDARD CARS IN FRONTAL CRASHES, NCSS

	AIS ≥ 2		AIS ≥ 3		Fatalities	
Source	N	%	N	%	N	%
Steering assembly	124	31	72	31	11	26
Other known source	133	33	66	29	6	14
Unknown source	142	36	91	40	26	60

3.2 The role of steering column intrusion

The accident statistics clearly indicate that the pre-Standard steering assembly was the number one injury source for drivers in frontal crashes. But what made it so dangerous? The first problem brought up in almost every discussion is the threat of "steering column intrusion." The pre-Standard steering column was, essentially, a rigid pole, rigidly attached to the car's front structure. When the front structure deforms rearwards in a frontal impact, it pushes the steering column upwards and backwards into the drivers chest, just like a battering ram.

The danger of column intrusion became apparent to engineers as a result of in-depth accident investigation programs such as ACIR. For example Figures 3-1 to 3-7 (in Section 3.7.1) clearly show the intrusion by the pre-Standard steering columns in highway accidents. In 1962, Burnstine discussed the danger of intrusion in a report on "Steering Wheel Impact" [9].

One year later, R.A. Wolf summarized ACIR data and highlighted steering column penetration as a cause of injury [76]. The risk of life-threatening or fatal injury in crashes with intrusion was twice as great as in crashes of similar severity with no column intrusion.

Huelke and Gikas, in their in-depth investigations of Michigan fatal accidents found that "the ram-rod effect produced by the backward movement of the steering column into the driver's area" was responsible for 18 of the 24 fatalities due to steering assembly contact. [35]. They felt these deaths could not have been prevented even if the drivers had used lap and shoulder belts.

The NCSS data confirm the strong association of steering column intrusion with steering contact injury. Table 3-5 shows that column intrusion (1 inch or more) occurred in only 3.5 percent of the pre-Standard frontal towaway crashes. Yet Table 3-6 shows that 20 percent of the steering contact injuries requiring hospitalization occurred in crashes with column intrusion. Of the more serious injuries (with AIS $\geq$ 3) 27 percent were in cars with column intrusion. These percentages do not include the crashes with "catastrophic or unspecified" intrusion, which also accounted for a large fraction of the injuries.

Table 3-5 shows that the likelihood of intrusion is highly correlated with Delta V. Among the cars with Delta V less than 15 mph, only 1.5 percent had column

TABLE 3-5

PRE-STANDARD STEERING COLUMN INTRUSION
IN FRONTAL CRASHES, BY DELTA V, NCSS

	Delta V				
	1-14	15-29	30+	Unknown	All Cases
Percent with column intrusion	1.5	6.8	24	2.3	3.5
Percent with no column intrusion	96.8	78.8	47	92.5	90.0
Percent with unspecified or catastrophic intrusion	1.7	14.4	29	5.2	6.5
N of cases	1724	863	72	1569	3951

TABLE 3-6

PRE-STANDARD STEERING COLUMN INTRUSION
INVOLVEMENT IN STEERING ASSEMBLY CONTACT INJURIES, NCSS

	Steering Contact Injury Severity	
	Fatal or Hospitalizing	Fat/Hosp with AIS≥3
Percent with column intrusion	20	27
Percent with no column intrusion	57	42
Percent with unspecified or catastrophic intrusion	23	31
N of injured drivers	124	62

intrusion and 1.7 percent had "unspecified" intrusion. When Delta V exceeded 30 mph, 24 percent of the cars had column intrusion and 29 percent had "catastrophic" or "unspecified" intrusion.

The NCSS data do not indicate whether intrusion was the "cause" of the injury. It is reasonable to assume, however, that in many of the cases in which there was fatal or hospitalizing steering contact and in which the column intruded, the intrusion increased the severity of the injuries. Also, in the cases of "unspecified or catastrophic" intrusion, the steering column may have moved rearwards together with other components and this may have contributed to the severity of the steering contact injury. Thus intrusion may have been a factor in up to 40 percent of the hospitalizing steering contact injuries and up to half of those with AIS $\geq$ 3 (see Table 3-6).

3.3 Characteristics of steering assembly contact injury

3.3.1 Body regions injured by steering contact

In a typical frontal crash, the driver's kinematics would cause chest contact with the steering wheel. Researchers initially concentrated on the problem of chest injuries. Because the steering wheel covers a fairly large vertical area and because additional vertical displacement may occur during intrusion, it became apparent that head or abdominal injury could result from contact with the upper or lower portion of the steering wheel.

Injuries to the chest, head and abdomen were evident in the multidisciplinary accident investigations conducted in the Sixties. Huelke and Gikas found the chest to be the most frequent location of fatal injury among 24 drivers killed due to steering assembly contact [35]. The head and abdomen had fatal lesions somewhat less frequently than the chest. Table 3-7 gives the fatal injury distributions.

The arms and legs can also be injured by contact with the steering wheel, column or mounts. Nahum, Siegel and Brooks' investigations of nonfatal accidents showed that 14 percent of the steering contact injuries were in the arms or legs [56]. Since minor injuries were included in the analysis, the head and neck were the most common location of nonfatal lesions, even outranking the chest. Table 3-8 gives the nonfatal injury distributions.

The NCSS data closely parallel these earlier studies. Table 3-9 shows the body regions of 778 drivers of pre and post-Standard cars who had steering contact injuries causing death or hospitalization. Since the pre and post-Standard car drivers had nearly the same injury distribution by body region, they were lumped to give a much larger sample of injured persons (see Section 6.3.2.). Only one injury per driver was included - the most severe steering contact injury if the driver had more than one of them.

Table 3-9 shows that the chest area is the most common location of steering contact injury, accounting for 41 percent of the fatal or hospitalizing injuries and 52 percent of the more severe lesions (AIS 3-6). The head and neck were the next most frequent location (26%), but the majority of these lesions, while requiring hospitalization, were not dangerous. Thus, the head and neck were the least common location (9%) of AIS 3-6 injury. The abdomen, on the other hand, ranked 2nd with 28 percent of the AIS 3-6 injuries, while ranking 3rd, overall (20%). The arms or legs were the location of 13 percent of the injuries requiring hospitalization and 11 percent of those with AIS 3-6.

TABLE 3-7

BODY REGIONS OF FATAL LESIONS DUE TO PRE-STANDARD STEERING ASSEMBLY CONTACT, MICHIGAN IN-DEPTH ACCIDENT INVESTIGATION

(Huelke & Gikas, 1966)

Fatal Steering Contact Injury Location	N of Drivers
Chest	10
Chest and abdomen	7
Chest and head	1
Head/neck	4
Abdomen	2

TABLE 3-8

BODY REGIONS OF NONFATAL LESIONS DUE TO PRE-STANDARD STEERING ASSEMBLY CONTACT, UCLA IN-DEPTH ACCIDENT INVESTIGATION

(Nahum, Siegel & Brooks, 1970)

Nonfatal Steering Contact Injury Location	Percent of Injuries*
Head/neck	40
Chest	33
Arms/legs	14
Abdomen	13

*Distribution of 148 individual steering contact injuries suffered by 82 drivers; includes minor injuries

TABLE 3-9

BODY REGION OF FATAL OR HOSPITALIZING STEERING CONTACT INJURIES, NCSS

Body Region	Fatal or Hospitalizing Injury	Fat/Hosp with AIS 1, 2 or Unk.	Fat/Hosp with AIS 3-6
	Percent of Drivers with Steering Contact Injury		
Chest/shoulder	41	28	52
Head/neck	26	47	9
Abdomen/pelvis	20	9	28
Arms/legs	13	6	11
N of drivers	778	349	429

3.3.2 Injury mechanisms

In 1969, Voigt and Wilfert completed a biomechanical reconstruction of 82 fatal head-on collisions and described the mechanism whereby steering assembly contact injures the driver [74]. Their findings are summarized below.

In the pre-Standard cars, the steering wheel was attached to the steering column by narrow, brittle spokes (Figures 3-22 and 3-23 in Section 3.7). The spokes or steering wheel rim could break completely when the driver contacted them and they became sharp objects that caused penetrating injuries (Figures 3-1, 3-3). Or they could just bend away, so that the full load of the driver was imposed on the narrow, rigid steering wheel hub (Figures 3-2, 3-4, 3-22, 3-23), causing blunt trauma.

An especially severe form of blunt trauma, called the "shovelling effect" by Voigt and Wilfert, occurs when the column moves upward relative to the driver after initial contact, "shovelling" the internal organs upward. This can happen both with and without column intrusion: with intrusion, if the column moves backward and then upward (Figures 3-4, 3-7);without intrusion, if the driver moves forward and then and then submarines downward (Figure 3-8).

Blunt trauma can also occur if the hub directly contacts the chest or abdomen (Figure 3-9) and results in a concentrated load that exceeds the tolerance of the ribcage or abdominal wall. There may be rib fractures and lesions to internal organs near the point of impact. Intrusion aggravates the injuries because it increases the relative velocity of the driver and the hub (Figures 3-2, 3-6, 3-7, 3-11).

The upper steering wheel rim can contact the head or neck, causing blunt trauma if the load exceeds the rather low tolerances of these body regions.

When the head has contacted the wheel and the driver's body continues to move forward, traction injury of the neck will result (Figure 3-10). The same thing will occur if the wheel continues to move backward due to intrusion (Figure 3-12).

Penetrating injury, as described above, is the result of broken rims and spokes. The location of the injury depends on where the broken spoke was during driver contact. When the spoke points downward, it is forced into the abdomen (Figure 3-3). Chest or facial injury results from other configurations.

The metal horn rings, hub covers, trim and hardware of pre-Standard steering wheels (Figure 3-22) were another source of lacerating and penetrating injury. When the steering wheel intrudes upward, severe facial injury may result from these metal objects (Figure 3-5).

The legs can be fractured or severely lacerated if the column or its supporting structures are a major lower body contact area. Arm, wrist or hand fractures may result from flailing against the steering wheel.

The NCSS cases generally do not contain enough information for a detailed biomechanical reconstruction. The file, however, contains numerous examples of steering contact injuries that would have resulted from the mechanisms described above. Appendix C lists all the cases of fatal or hospitalizing steering contact injury.

3.3.3 Principal direction of force

The principal direction of force (PDOF) experienced by the crash-involved vehicle directly affects the driver's kinematics. The driver's movement generally parallels the force vector. Accident investigators classify PDOF in 12 30-degree zones called "clock directions" - i.e., a 12:00 impact is one whose PDOF is directly frontal or within 15 degrees of either side of direct frontal [11]. A 1:00 PDOF is anywhere between 15 and 45 degrees to the right of frontal, and so on.

In 12:00 impacts, many drivers will move straight ahead into the steering wheel, more or less parallel with the steering column (unless there is substantial vehicle rotation, driver misposition or lateral rotation of the column due to damage). Thus, a steering column designed to absorb energy under axial load has a good chance to perform as designed. In 11:00 and 1:00 impacts, on the other hand, the driver will usually not move in a direction parallel to the steering column and an energy absorbing device requiring axial load will have less chance of successful performance. It is important to know the PDOF distribution of steering contact injuries because the higher the percentage of injuries involving PDOF other than 12:00, the more attention must be given to devices that absorb energy under nonaxial load.

Table 3-10 shows, however, that crashes with PDOF other than 12:00 accounted for only 23 percent of the pre-Standard steering contact injuries, even though they represented 44 percent of the frontal crashes. The risk of injury by the steering assembly was nearly 3 times as high in a 12:00 impact as in other frontal impacts. By contrast, there were no differences by PDOF in the injury risk from other contact sources. In the nonaxial crashes, the drivers were more likely to receive their serious injuries from contacts other than the steering assembly.

Because 77 percent of the fatal or hospitalizing steering contact injuries occurred with 12:00 PDOF, this category of crashes deserved highest priority in the development of remedies.

TABLE 3-10

PRINCIPAL DIRECTION OF FORCE IN FRONTAL CRASHES AND IN FATAL OR HOSPITALIZING STEERING CONTACT INJURIES, NCSS

(Pre-Standard 203 and 204 passenger cars)

PDOF	Percent of Fat/Hosp Steering Injuries	Percent of Frontal Crashes	Injury Rate (%)
12:00	77	56	4.4
11:00 or 10:00	13	25	1.6
1:00 or 2:00	10	19	1.6
N of cases	124	3951	3.1

3.3.4 Delta V distribution

Delta V is a measure of collision severity. It is the magnitude of the vector denoting the crash-involved vehicle's velocity change during the impact. The CRASH accident reconstruction program was used to estimate Delta V on NCSS [49].

Table 3-11 shows the Delta V distributions of pre-Standard vehicles involved in frontal crashes and of those in which drivers suffered fatal or hospitalizing steering contact injuries. The injury risk rises sharply with increasing Delta V, ranging from 0.5 percent when Delta V is less than 10 mph to 50 percent when Delta V is 40 or more. On the other hand, the high-speed crashes are much rarer than those at moderate speed. As a result, the cumulative Delta V curve for the injuries rises at a moderate, steady rate throughout the 10 - 35 mph range: the 25th percentile of cumulative Delta V, for injured drivers, is 15 mph. The median is 22 mph. The 75th percentile is 29 mph. The Delta V distributions for drivers with steering contact injury does not differ substantially from the Delta V distribution for all types of injured occupants in frontal crashes. (See [69], pp. 88-89.)

TABLE 3-11

DELTA V DISTRIBUTION IN FRONTAL CRASHES AND IN FATAL OR HOSPITALIZING STEERING CONTACT INJURIES, NCSS

(Pre-Standard 203 and 204 passenger cars)

Delta V Range mph	Fat/Hosp %	Steering Injuries Cumul. %	Frontal Crashes %	Frontal Crashes Cumul. %	Injury Risk (%)
1 - 9	6	6	39	39	0.5
10 - 14	18	24	33	72	2
15 - 19	15	39	14	86	4
20 - 29	39	78	11	97	13
30 - 39	14	92	2.4	99.4	22
40 +	8	100	0.6	100	50
N of drivers	89		2382		

3.4 Standards 203 and 204

3.4.1 Remedies that preceded the standards

Accident investigation and engineering of the early 1950's showed that drivers were being injured because their load was imposed on the narrow, rigid steering wheel hub. The deep dish steering wheel was introduced in some 1956 models in order to keep the driver from contacting the hub [76]. It subsequently became commonplace on passenger cars (See Figure 3-23). Its objective was to initially concentrate the driver's load on the steering wheel rim, which was more flexible than the hub. As late as 1962, Burnstine felt that the deep dish steering wheel improved crashworthiness significantly [9]. In 1963, however, based on further accident investigation, R.A. Wolf concluded that the deep dish wheel could not prevent hub contact in a severe collision (Figures 3-3 and 3-4) [76]. Also, it did not deal with the problem of steering column displacement into the passenger compartment.

In 1959, the Saginaw Steering Gear Division of General Motors began to design a steering column that could absorb energy while telescoping [47]. It took many years of research and testing to achieve a successful design, partly because the steering column is a complex device incorporating several functions. GM's first design was the "Invertube," an aluminum tube that would be forced inside out while the column was telescoping. It did not perform too well in GM's tests. GM's next design was the "Japanese Lantern." The steering column jacket contained a 6 inch slotted portion which would fold in like a Japanese lantern, and absorb energy as the column telescoped. At about this time, GM engineers realized that the device would need to serve the twin purpose of absorbing the driver's load and resisting intrusion, so they designed a prototype of the <u>shear capsule</u> (which is described in Section 3.4.3). The Japanese Lantern performed well in tests, but it did not possess enough crush distance or force-deformation uniformity. It was replaced by the "diamond-mesh" device, which offered 8.25 inches of collapse and folded in 5 places instead of 1. With the addition of the telescoping, engine-compartment anti-intrusion device, the Saginaw Steering Gear Division had developed a column whose performance characteristics are echoed in Standards 203 and 204.

The Ford Motor Company developed padding for the steering wheel hub and installed it in their 1967 passenger cars [50].

The Cornell Aeronautical Laboratory, based on crash testing, biomechanical research, and ACIR accident data, presented designs for energy absorption and reduced intrusion in 1964 (see Figure 3-25 and [75]). Subsequently, they developed test procedures and specifications which were eventually incorporated into safety regulations [8].

3.4.2 Regulatory history of Standards 203 and 204

In December 1965, the Society of Automotive Engineers (SAE) issued Recommended Practice J944, a bench test of steering column energy absorption ([61], pp. 923-925). A torso shaped body block (the "black tuffy"), weighing 75-80 pounds and having a spring rate load of 600-800 pounds per inch, impacts a steering assembly mounted at the manufacturer's installation angle. Load cell recording devices are mounted between the body block and the energy absorbing device in the column or steering wheel. J944 is a test procedure only: it does not specify a maximum acceptable load.

The General Services Administration (GSA) had a Standard 515 concerning safety devices in Federally purchased motor vehicles. In March 1966, the GSA proposed its Standard 515/4a, which specified performance requirements for steering column energy absorption and intrusion prevention [20]. The energy absorption clause specified that the force developed on the load cell recording device must not exceed 2500 pounds when a body block travelling 22 feet per second (15 mph) contacts the steering assembly in a J944 test. The anti-intrusion clause specified that the upper end of the steering assembly must not be displaced horizontally rearward more than 5 inches at any time during or after a 30 mph frontal barrier crash test (SAE Recommended Practice J850 - see pp. 915-6 of [61]). The proposed standard also specified that horn actuating mechanisms and other steering wheel attachments be designed so as not to catch the driver's clothing or jewelry during normal driving.

The GSA's proposed Standard 515/4a became a final rule in July 1966, with an effective date of October 1967 [21]. All passenger cars purchased by GSA after the latter date were required to comply with the standard.

NHTSA extended the GSA standard, without significant changes, to all passenger cars sold in the United States. The body block test and the clause on steering wheel attachments became the performance requirements of Federal Motor Vehicle Safety Standard 203. The 5 inch limit on rearward intrusion during a 30 mph barrier test became Standard 204. A Notice of Proposed Rulemaking, which included both standards, was published in the Federal Register in December 1966 [22]. The final rule was adopted in February 1967, with an effective date of January 1, 1968 [23]. All cars manufactured after that date, for sale in the United States, had to comply with both standards.

All domestic 1967 GM, AMC and Chrysler cars were equipped with energy absorbing devices. All 1968 model cars are believed to have met the Standards.

Standards 203 and 204 have remained essentially unchanged since 1967. A 1970 proposal for much more stringent requirements in the body block test was never adopted [24].

3.4.3 Safety improvements made in response to Standards 203 and 204

The two preceding sections showed that Standards 203 and 204 were the culmination of a cooperative effort by the motor vehicle industry, research institutions and the government. The result was a large number of steering assembly safety improvements implemented more or less at the same time. The philosophy of this evaluation is to regard all of these improvements as having been made "in response to" Standards 203 and 204 and to avoid speculation as to which items were minimally "required" for compliance and which ones were "voluntarily" installed by manufacturers (see Section 1.2). Such speculation is especially inappropriate here, because the manufacturers themselves did much of the work leading up to the Standards before NHTSA was founded.

Nevertheless, it is evident that some of the modifications are closely linked to the performance requirements. These will be described first.

Figure 3-13 shows a "generic" post-Standard steering assembly. It is helpful in locating the various hardware items.

The steering column energy absorbing device (EAD) is located between the instrument panel and the firewall. The steering column contains several components: the steering shaft, the shift tube, the jacket, etc. One of the components, normally the jacket, is designed to absorb energy at a controlled rate when the column is compressed. The steering column EAD has 2 purposes:

- If the bottom of the column is pushed upwards as a result of frontal vehicle damage, the column becomes shorter. Thus, the steering wheel does not intrude rearwards.
- *If the driver contacts the steering wheel, the column shortens at a* controlled rate, absorbing the driver's load at a nondangerous force-deflection level.

Several alternative devices have been used to absorb energy (See Figure 3-14). The mesh type EAD was originally used in GM, Chrysler and AMC cars (see Figures 3-15 and 3-17). The steering column jacket contains 5 diamond-shaped sections of metallic mesh which crumple one by one under load (see Figure 3-16). Ford initially used a slotted column which worked on the same principle. (Figure 3-14, item 5) These columns allowed about 8 inches of crush.

The mesh and slotted columns were somewhat bulky and difficult to fabricate. They had an uneven force deflection characteristic because the mesh sections collapsed one by one. They tended to bind under nonaxial impact [48]. To remedy these faults, the Saginaw Steering Gear Division developed the ball type column for GM and AMC. Here, the jacket contains concentric tubes that resist telescoping. The resistance is caused by steel balls in the space between the tubes (commonly 16 balls). The balls are larger than the distance between the tubes. When the column collapses, the balls gouge grooves into the tubes as they roll axially during the telescoping motion (Figure 3-17). Since the ball column depends on developing a friction force between concentric tubes, it, too, is susceptible to binding under nonaxial load.

Ford accomplished basically the same objective with its "mini" and "Mod I" columns. Here, the concentric tubes are forced through a ring. The ring has some protrusions that gouge grooves into the tubes as they telescope (Figure 3-14, item 8). These columns are not designed to collapse as a result of frontal vehicle damage: a plate attached to the tubes just below the ring prevents the tubes from passing upwards through the ring. Thus, these devices are designed to collapse only under occupant loading.

Chrysler developed a slotted jacket and mandrel column to replace the mesh type. The mandrel is a rigid device attached to the firewall. It crushes the slotted jacket during column compression, causing extrusion of the jacket (Figure 3-18).

Most imported cars initially had the mesh type. Many makes and models subsequently adopted the ball type column [54].

The shear capsule or an equivalent device for attaching the column to the instrument panel is a vital partner to the steering column EAD (Figure 3-19). The shear capsule is a bracket designed to prevent rearward movement of the column but to allow forward movement. Thus, when the lower part of the column is forced backward due to vehicle damage, the shear capsule holds the upper column in place while the column EAD collapses. On the other hand, when the driver contacts the steering wheel, the shear capsule freely allows the upper part of the column to move forward while the EAD collapses. The Ford "mini" column is not equipped with a shear capsule, since it is not designed to collapse due to vehicle damage.

In a severe frontal crash, the rearward motion of the lower part of the column may exceed the potential collapse distance available in the column EAD. Thus, in many makes and models, another telescoping device, providing typically 8 inches of additional crush distance, was installed in the engine compartment portion of the column (Figures 3-18 and 3-20).

In certain cars, the engine compartment section of the column contains a series of universal joints. They sometimes have the effect of translating rearward motion of the steering gearbox into vertical motion of the upper column. Thus, the steering assemblies comply with Standard 204 (which limits rearward intrusion to 5 inches) even though up to 10 inches of vertical intrusion may occur in the compliance tests of some of the smaller imported models [31].

The steering wheel EAD is a device for absorbing the driver's load which was used in a small number of makes and models sold in the United States (Figure 3-21). A convoluted metal canister is located directly beneath the steering wheel hub. When the driver contacts the wheel, the canister folds like an accordion and crumples. In this process, the steering wheel aligns itself to the driver's body. Thus, the steering wheel EAD provides effective energy absorption even in nonaxial impacts. The device is not designed, however, for preventing rearward column intrusion. An engine compartment telescoping device, or its equivalent, is required for Standard 204 compliance.

A few makes and models - principally 1974-78 Volvos and 1972-74 Volkswagens - were equipped with wheel and column EAD's [54].

The Fiat 850 and certain BMW models were equipped with neither wheel nor column EAD's. They relied on flexibility in the steering wheel spokes, the column and the supporting structures to absorb energy.

Table 3-12 is a summary of steering wheel and column EAD types in high-volume makes and models.

Steering wheels were made much safer at about the same time that the EAD was installed. The pre-Standard steering wheel (Figures 3-22 and 3-23) presented major hazards in its narrow, rigid hub; thin, brittle spokes; and metallic attachments including the horn ring. (The role of these items as sources of injury is discussed in Section 3.3.2.) These hazards were generally eliminated in post-Standard wheels (Figure 3-24). The hub and spokes were integrated to provide a single, broad padded surface over which the driver's load could be more safely distributed. The spokes were made wider, stronger and less brittle. Often, a third spoke was added to increase spoke/rim integrity. Horn rings and other sharp metal trim were generally absent. The diameter of the rim was often smaller, reducing the likelihood of facial and abdominal contact.

TABLE 3-12

TYPES OF STEERING COLUMN AND WHEEL ENERGY ABSORBING DEVICES, BY PASSENGER CAR MAKE, MODEL AND MODEL YEAR, 1967-78

Device	Manufacturer/Make	Product Line	Model Years
Mesh column EAD	GM	All domestic	1967-68
		Corvair	1967-69
		Opel	1967-74
	AMC		1967-69
	Chrysler Corp.	All (except 70-73 Barracuda, Challenger Colt)	1967-73
Ball column EAD	GM	All domestic (except Corvair 1969)	1969-78
	AMC		1970-78
	Dodge	Colt	1970-74
Slotted column EAD	Ford Motor Company	Full size (except Thunderbird)	1968-78
		Maverick/Comet	1968-77
		Mustang	1968-73
		Intermediates	1968-71
		Thunderbird	1968-71
Grooved column EAD	Ford Motor Company	Pinto/Bobcat	1971-78
		Intermediates	1972-78
		Thunderbird/Mark	1972-78
		Mustang	1974-78
		Fairmont/Zephyr	1978
Slotted jacket & mandrel (column EAD)	Chrysler Corp.	All (except 1974 Barracuda & Challenger)	1974-78
Steering wheel EAD	Mercury	Capri	1971-76
	Plymouth	Barracuda	1970-74
	Dodge	Challenger	1970-74
Steering wheel EAD and column EAD	Volvo	All passenger cars	1974-78
	Volkswagen	All passenger cars	1972-74
Hub pad only (Does not meet Stds. 203 and 204)	Ford Motor Company	All passenger cars	1967

Sources [50, 54, and 59]

Since, however, the performance test of Standard 203 does not necessarily require an improved wheel for compliance, the improvements were not universal. In some "sporty" cars, the small, round hub and thin metal spokes were retained for cosmetic reasons (Figure 3-37).

The removal of horn rings and metal trim may have been motivated by the clause in Standard 203 which states that these items must not catch the driver's clothing or jewelry.

During the 1960's, the trend in passenger car styling was "longer and lower." As a result, the angle of the steering column tended to become somewhat closer to horizontal. The driver would thus be more likely to contact the steering assembly axially. Since steering column EAD's work best under axial impact, the styling changes may have resulted in some safety benefits.

Another design change of the 1960's was the introduction of forward-mounted steering gearboxes in some makes and models [72]. In combination with longer hoods and wheelbases, this provided additional room in the engine compartment for telescoping devices and universal joints.

3.5 Engineering discussion

Why did the engineers design the energy absorbing steering assemblies the way they did? The question can be better understood after a brief review of the mechanics of frontal collisions.

Consider a passenger car travelling 25 miles per hour, with an unrestrained driver, striking another car of the same size, at the same speed, head-on. Within the short time span of the collision, 2 nearly independent events transpire. First, the car is brought to a stop. At the end of this event, however, the driver is still moving forward at close to 25 mph. His destination is a stationary steering wheel, instrument panel, windshield, etc. In the second collision, the driver contacts these hardware items at 25 mph and they bring him to a stop. His kinetic energy is dissipated within the limited areas that his body and the hardware are in contact. It is dissipated when something yields and absorbs energy – either his body or the hardware.

The likelihood of driver injury is reduced by

- reducing the speed of the "second" collision of the driver with the hardware – reducing the driver's kinetic energy.
- increasing the contact area of the second collision – spreading the forces.
- designing the hardware to yield at a force level that is not dangerous to the human body.

The speed of the second collision can be reduced by beginning the process of slowing down the driver during the first collision – while the vehicle is still moving. A linkage must be created between the driver and the vehicle. The driver may obtain some degree of linkage by using seat belts and bracing himself during the crash.

The engineer's job is to see that the speed of the second collision is, at least, not increased. He must prevent rearward intrusion of the steering assembly. Why does intrusion increase the speed of the second collision? Consider the head-on crash described above. Suppose that the steering assembly attaches itself to the front of the other car, which is moving at 25 mph. Then the steering wheel would be intruding rearwards at 25 mph, while the driver is still travelling forwards at 25 mph, i.e., the second collision has begun before the first collision has ended. The driver would contact the steering wheel at a relative speed of 50 mph in this extreme case. The risk of injury is incomparably greater than in the nonintrusion crash, where the relative speed was 25 mph.

Whereas this extreme case, in which the steering assembly simply attached itself to the front of the other car, is unrealistic, films of crash tests show that intrusion, when it does occur, can result in large column velocity relative to the driver.

The engineer's first priority is to prevent rearward intrusion by using telescoping devices in the column or by completely breaking the linkage between the steering gearbox and the steering wheel.

The <u>contact area</u> of the second collision was obviously increased by the improved design of post-Standard steering wheels. The broad, integral hub and spokes spread the forces. The stronger spokes resist breakage- sharp, broken spokes are a contact area so narrow that penetrating injury can occur. A second method to increase contact area is to design and position the wheel so that it contacts the body over a wide area, not just one spot on the rim. The rim and spokes should flex back somewhat, to increase the contact area, but they should not bend away completely because this would concentrate loads on the hub. In other words, there are trade-offs on their strength.

The steering wheel EAD is the ultimate development in a steering wheel that aligns itself to maximize contact area.

A third method to increase contact area is to design the instrument panel to absorb a larger portion of the driver's load. The legs can withstand greater forces than the head and trunk. The knee bar on Volkswagen Rabbits equipped with automatic restraints was designed for this purpose.

Steering column intrusion again increases risk because it reduces contact area. Rearward intrusion is the worst because the driver's chest contacts the wheel before his knees strike the instrument panel. As a result, the driver's load is concentrated on the chest-wheel contact. Upward intrusion is also undesirable because it causes the steering wheel to pivot from a nearly vertical plane to a more horizontal one. As a result, the driver contacts a narrow area on the rim rather than the broad, flat face of the post-Standard hub.

Finally, the energy absorbing devices in the column and wheel were obviously designed to make the hardware yield at a force level that is not dangerous to the human body. The difficulty in designing these devices lay in the many trade-offs, constraints and practical engineering problems they involved.

The amount of the driver's kinetic energy that a device can absorb is the product of its force deflection characteristic and available crush distance. The latter is a major design constraint - there is a limit on how much crush distance can be furnished within the confines of the passenger compartment. By far the longest potential collapse distance is available in the portion of the steering column between the instrument panel and the firewall. As a result, engineers initially concentrated on developing the column EAD. This device, however, presents an engineering problem which limits its versatility: although many variations of the column EAD have been built, all have a tendency to bind, or jam, rather than telescope when the driver impacts them nonaxially. For example, nonaxial contact occurs if the crash forces on the vehicle are not purely frontal (see Section 3.3.3), or when crash damage displaces the column alignment - especially during upward intrusion - or if the driver is somewhat out of position. Locking up of telescoping column components other than the EAD - e.g., the steering shaft or the shift tube - can also lead to column noncompression.

The steering wheel EAD was considered promising because it collapses successfully even in nonaxial impact. But this device is limited in the amount of crush distance that can be made available. It is not effective in preventing intrusion - so telescoping devices are still required in the lower column. Finally, acceptance of the steering wheel EAD may have been limited by styling concerns.

The conflict could have been resolved by installing both the wheel and column EADs. Obviously, the cost of providing both devices may have discouraged this approach except in a few models.

The other parameter that must be considered is the force-deflection characteristic of the EAD. If it is set too low, all of the collapse distance would be used up in a severe impact without absorbing the driver's kinetic energy. There would be a risk of dangerous injury. If it is set too high, serious injury could result to the more sensitive body regions, such as the abdomen and head, in crashes of relatively low severity.

The compliance test for Standard 203 dictates a rather high force-deflection characteristic for the EAD, given the mass of the torso block used in the test, the test speed, and the collapse distance available. "Rather high" means, in this context, about as much as the human chest can absorb without significant injury. This is more than the head or abdomen can tolerate. The Standard writers felt that a severe crash with steering assembly loads concentrated on the head or abdomen was a rare event.

The steering wheel hub and spokes were padded to absorb energy in low severity crashes and in case of initial contact by the head, arms or abdomen. The wheel rim and spokes were made somewhat flexible and energy-absorbing for the same reason. These measures were used to complement the relatively high stiffness of the EAD.

Upward intrusion of the column increases risk for reasons related to energy absorption, too. Upward intrusion is strongly associated with binding of the column EAD. Furthermore, it increases the likelihood that the driver's head will contact the wheel before the rest of his body contacts anything.

A final tradeoff that must be considered is the possibility of increased risk of injury by components other than the steering assembly. If the EAD collapses too easily, it could allow the driver to contact the windshield, instrument panel, etc., while he still has considerable kinetic energy.

These were the primary considerations expressed by engineers concerning the design of a crashworthy steering assembly. The actual performance of the designs - including a comparison of field performance to the judgments described above - will be discussed in Chapters 5 and 6. In summary, though, the chief concerns of engineers regarding the current designs appear to be

- Binding of the column EAD or other steering assemly components under nonaxial load
- Hazards associated with upward intrusion
- Risk of head or abdominal injury
- Contact forces are concentrated on a small area

Sections 3.7.4 and 3.7.5 pictorially document the successful and unsuccessful performance, respectively, of post-Standard steering assemblies in highway accidents.

3.6 Other standards that protect drivers in frontal crashes

There are 8 other Federal Motor Vehicle Safety Standards that reduced the injury risk of drivers in frontal crashes. Their benefits must be taken into account in this evaluation and should not be wrongly attributed to Standards 203 and 204 (see Section 5.2.4).

- Standard 201 required padding of specified interior surfaces, especially the instrument panel, which may be contacted by drivers in frontal crashes. It is unlikely, however, that Standard 201 had much influence on the risk of steering assembly contact injury.

- Standard 205 required a crashworthy windshield and Standard 212 was designed to prevent ejection through the windshield area. These standards, however, are unlikely to have affected the risk of steering contact injury.

- Standard 207 was designed to prevent seat failure. If the seat fails in a frontal crash, it can move forward with the driver and increase his load on the steering wheel. Thus, it is conceivable that Standard 207 has reduced steering contact injury. The reduction, if any, is small. The Standard's performance requirements apparently did not result in vehicle modifications other than seat back locks in 2 door cars [7]. The effect of seat back locks in reducing driver injury in 2 door cars, based on preliminary analyses, appears to be very small [6].

- Standards 208, 209 and 210 have been associated with an increase in belt usage over 11 model years, beginning in 1964. The use of a lap belt can modify the alignment of the driver's body when he contacts the steering wheel, resulting in improved EAD collapse (Figure 3-32). It can reduce the velocity of the "second" collision of the driver with the steering assembly (see Section 3.5). The driver who uses the lap and shoulder belts may occasionally be able to avoid steering assembly contact entirely. Thus, an increase in belt usage has led to a decrease in steering assembly contact injury.

- Standard 214 led to stronger side doors. This standard has been effective in side door impact crashes with frontal force components [37]. It is unlikely, however, that it reduced the risk of steering assembly contact injury.

3.7 Pictorial review of Standards 203 and 204

3.7.1 Pre-Standard steering assembly performance

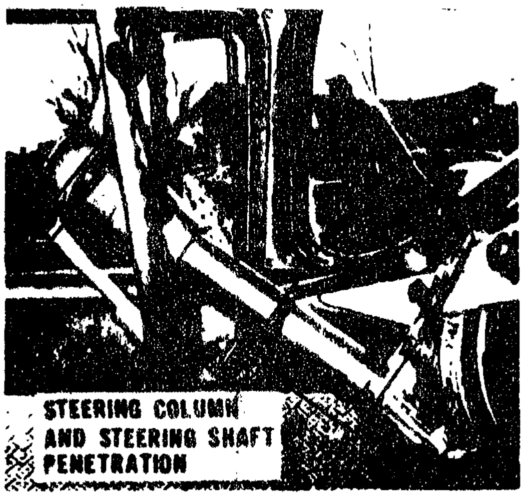
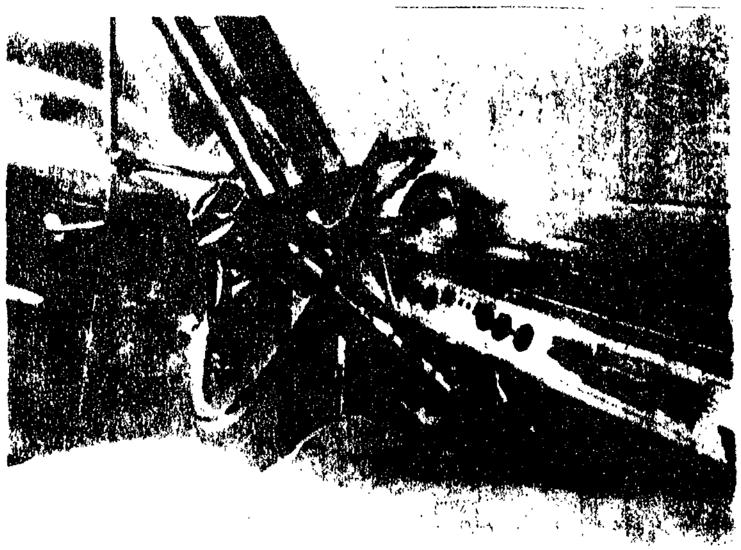


FIGURE 3-1: Rearward column intrusion with steering wheel rim and spoke failure. As the intruding steering assembly strikes the driver's chest, the brittle spokes break. Crash forces are concentrated on the rigid, narrow hub and the pointed broken spokes [75].

FIGURE 3-2: 1954 Ford struck embankment at 25 mph. Rearward column intrusion and complete bending away of rim and spokes. Note the dangerous shape of the hub, which absorbed the driver's load. There were fatal chest injuries [34].



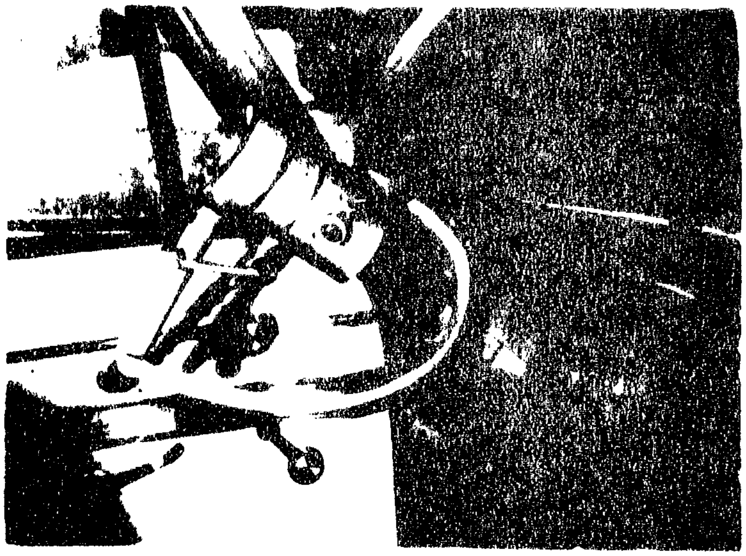
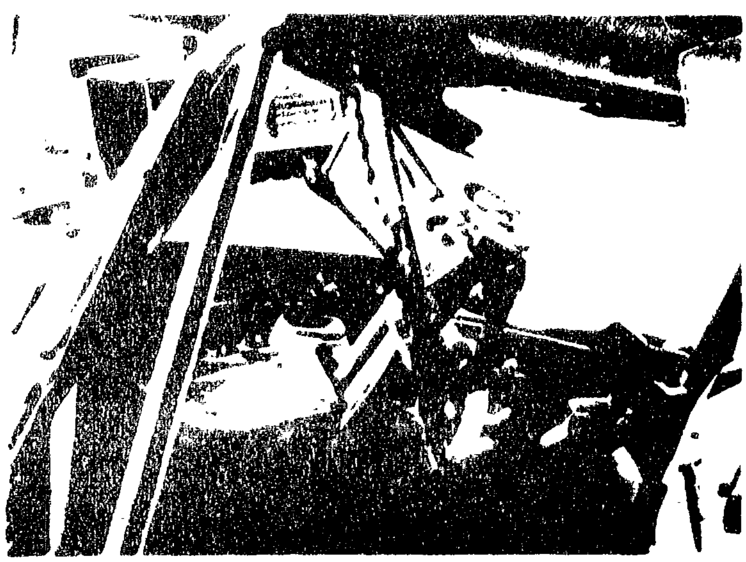


FIGURE 3-3: Rearward intrusion with rim and spoke failure. Note how spokes became "battering rams." Multiple fatal chest and abdominal injuries. 1965 Chevrolet in head-on collision with 50 mph impact speed [34].

FIGURE 3-4: 1962 Ford struck a tree at 45 mph. Rearward and upward intrusion with steering wheel failure. The rigid, narrow hub "shovelled" the driver's internal organs upwards, causing massive fatal chest and abdominal injuries [34].



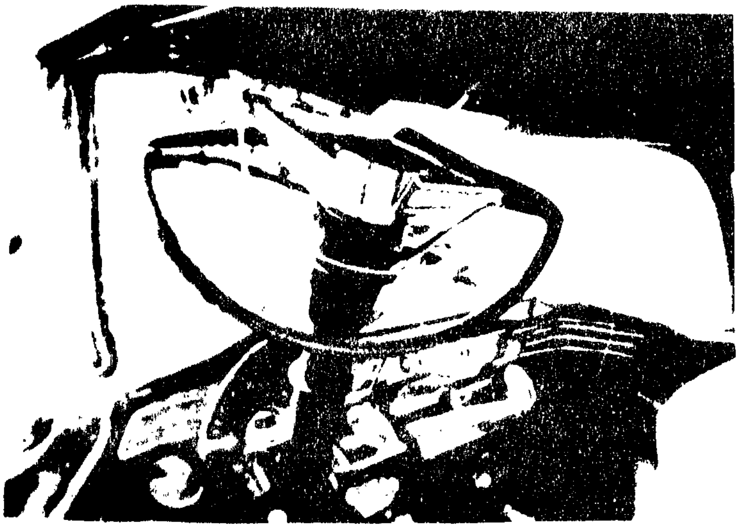


FIGURE 3-5: 1956 Pontiac in 35 mph head-on collision. Extensive upward column intrusion. The metal horn ring caused severe facial injuries [34].

FIGURE 3-6: Extensive sideways and rearward intrusion with partial failure of the steering wheel rim during driver contact [9].

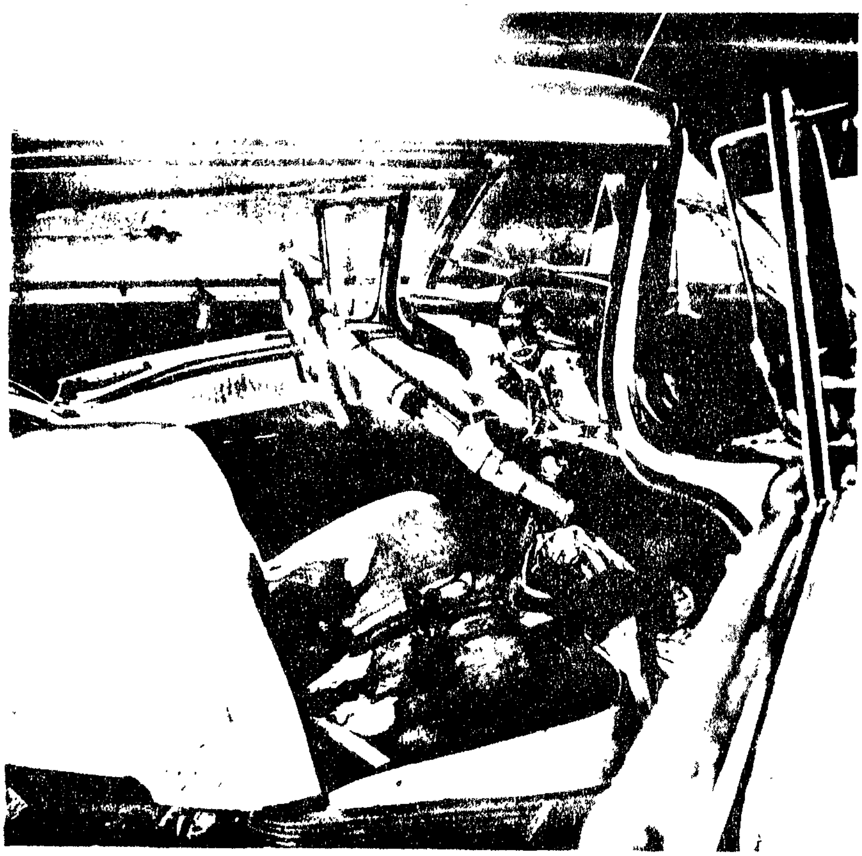


FIGURE 3-7: Catastrophic frontal impact including failure of firewall, instrument panel and seat. The rigid steering column intruded through the driver seating area and nearly reached the roof above the front seat. The steering wheel was completely separated from the column [9].

3.7.2 Steering assembly contact injury mechanisms

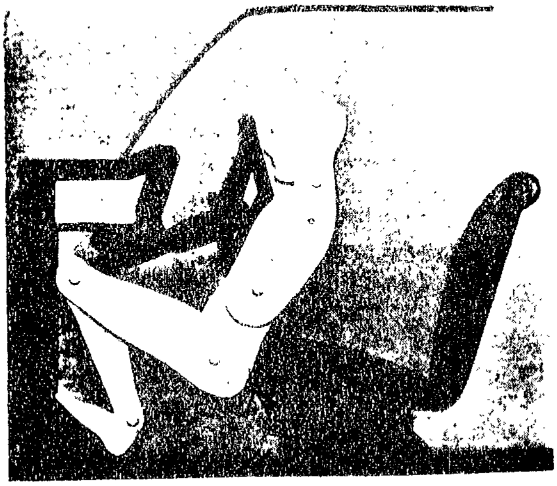


FIGURE 3-8: The narrow, rigid hub initially contacts the upper abdomen. The thoracic organs are "shovelled" upwards by the driver's submarining movement or the upward intrusion of the column [74].

FIGURE 3-9: The hub initially contacts the chest. Thoracic injuries are aggravated when the driver's load is concentrated on the narrow hub or sharp, broken spokes [74].

FIGURE 3-10: The upper part of the rim may cause head injury. Neck injury occurs if the torso continues to move forward while the head is held back by the steering wheel. Metallic horn rings aggravate facial injuries [74].

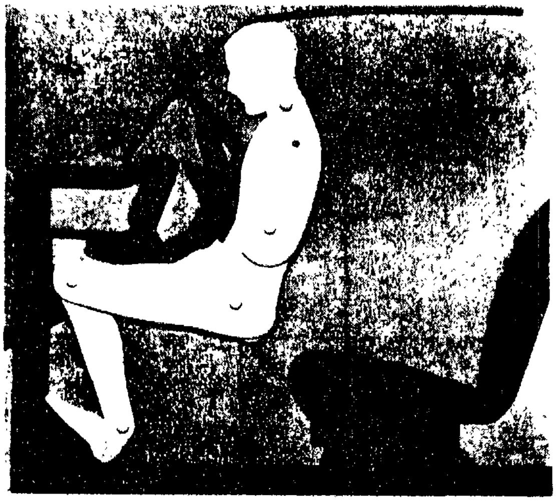


FIGURE 3-11: Rearward column intrusion aggravates thoracic injuries because the dynamic load on the driver's chest is higher than in nonintrusion cases of similar vehicle velocity. Broken spokes cause abdominal injury [74].

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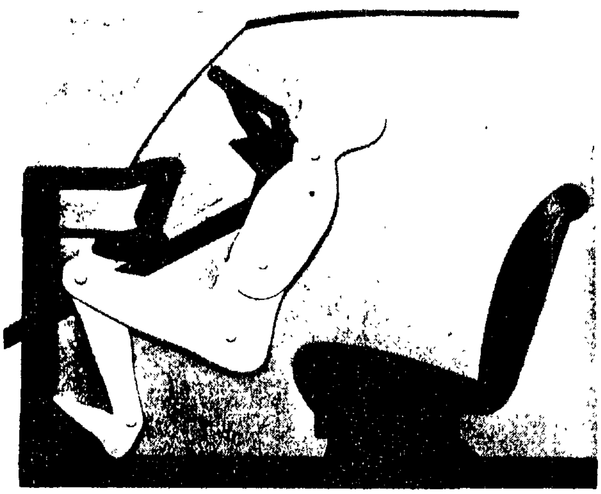

FIGURE 3-12: Rearward and upward column intrusion aggravates head and neck injuries [74].

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NOT PICTURED: (1) Abdominal injury from rearward and downward column intrusion.

(2) Arm injury from contact with unpadded steering wheel hubs, rims and spokes or metallic horn rings.

(3) Leg injury from column contact.

3.7.3 Equipment installed in response to Standards 203 and 204

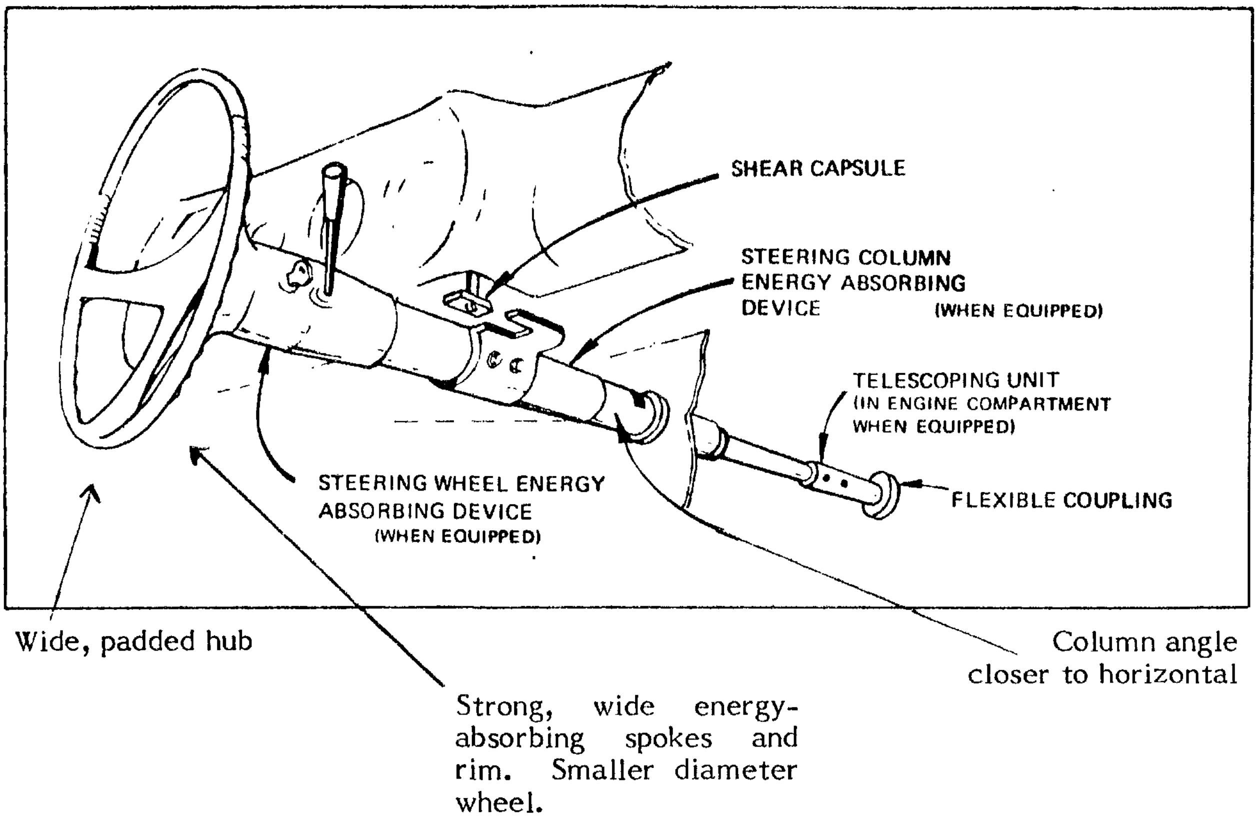
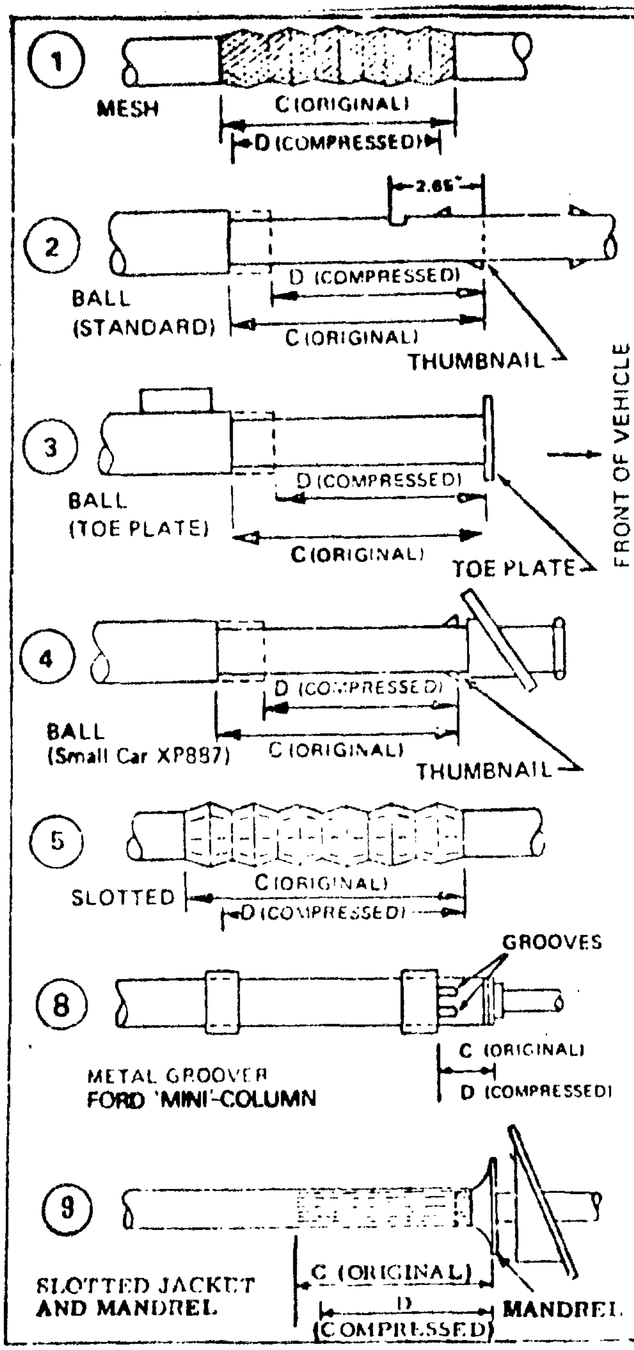


FIGURE 3-13: Equipment installed or modified in response to Standards 203 and 204. The "steering wheel energy-absorbing device" was only installed on a small number of makes and models. Figures 3-14 to 3-24 offer detailed views of the devices shown above [54].



70-73	Chrysler Products, Except Barracuda and Challenger and Colt	67-68 GM 67-69 AMC
70-74 70-74	AMC Products GM Products Except Those Lines Listed Below	
70-74	Chevrolet Corvette	
71-74	Chevrolet Vega	
70-74	Ford Products Except Those Lines Listed Below	
71-74 72-74 74	Ford Pinto Ford Torino Ford Thunderbird Mercury Montego Lincoln Mark IV Ford Mustang II Mercury Cougar	
74	Chrysler Products Except Barracuda and Challenger and Colt	

FIGURE 3-14: Variations of the Steering Column Energy-Absorbing Device used in domestic vehicles. Most foreign models employ designs similar to one of the above. Ford has gradually shifted its production from the slotted type to the grooved type [54].

FIGURE 3-15: Mesh-type column as installed in a 1967 GM car. Note hardware required to support the column - this motivated GM to shift to the more easily supported ball type column [48].

FIGURE 3-16: Post-crash view of the mesh-type device in a 1967 Chevrolet. The column collapsed 4 inches. Note how the mesh collapses in sections [34].

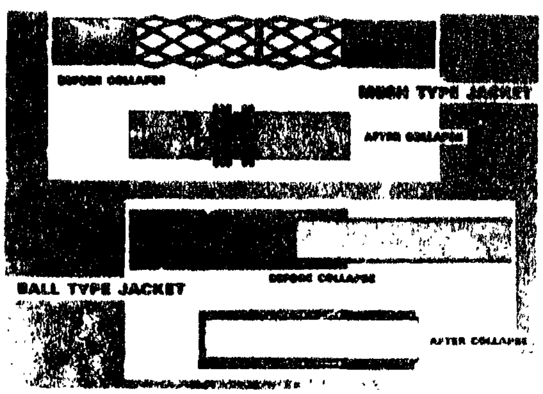


FIGURE 3-17: Comparison of telescoping action in mesh and ball type columns [48].

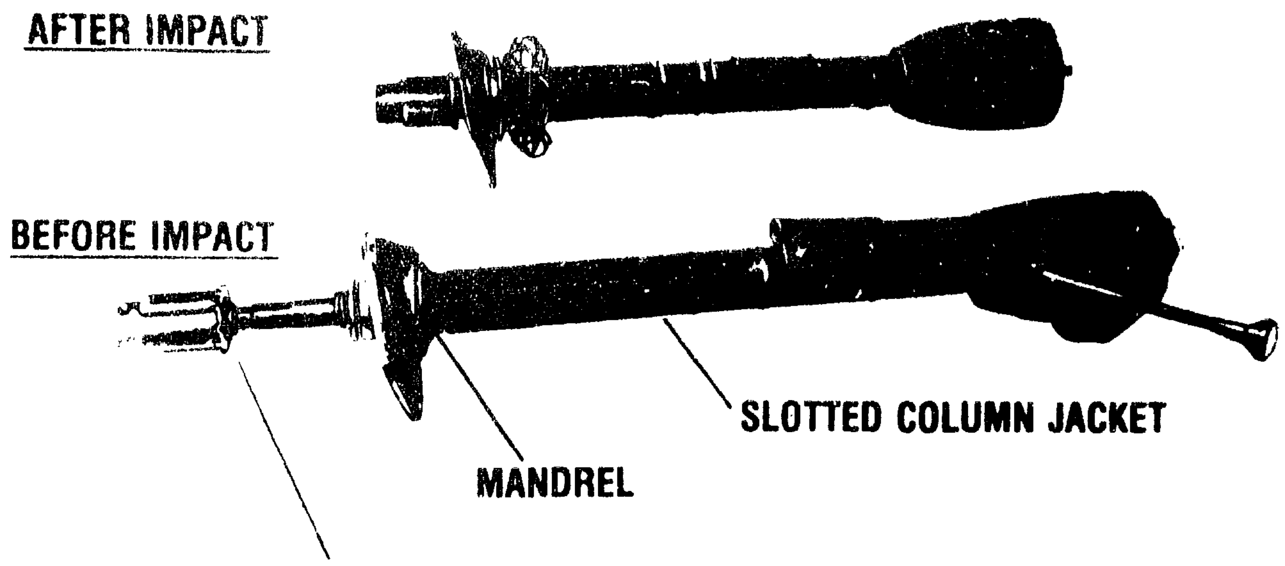
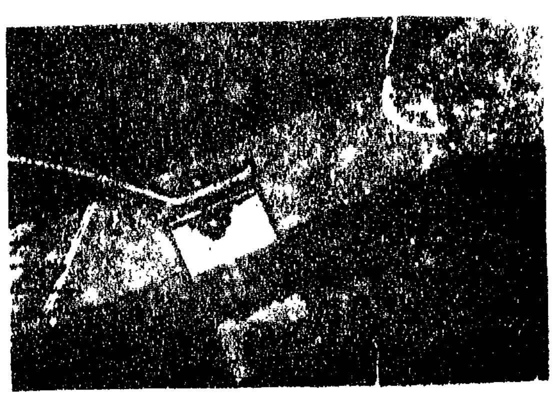


FIGURE 3-18: Slotted-jacket column used in Chrysler cars since 1974. The post-impact photograph shows that both the upper column and the engine compartment unit telescoped and how the slotted jacket crumples on the mandrel [59].

Side View

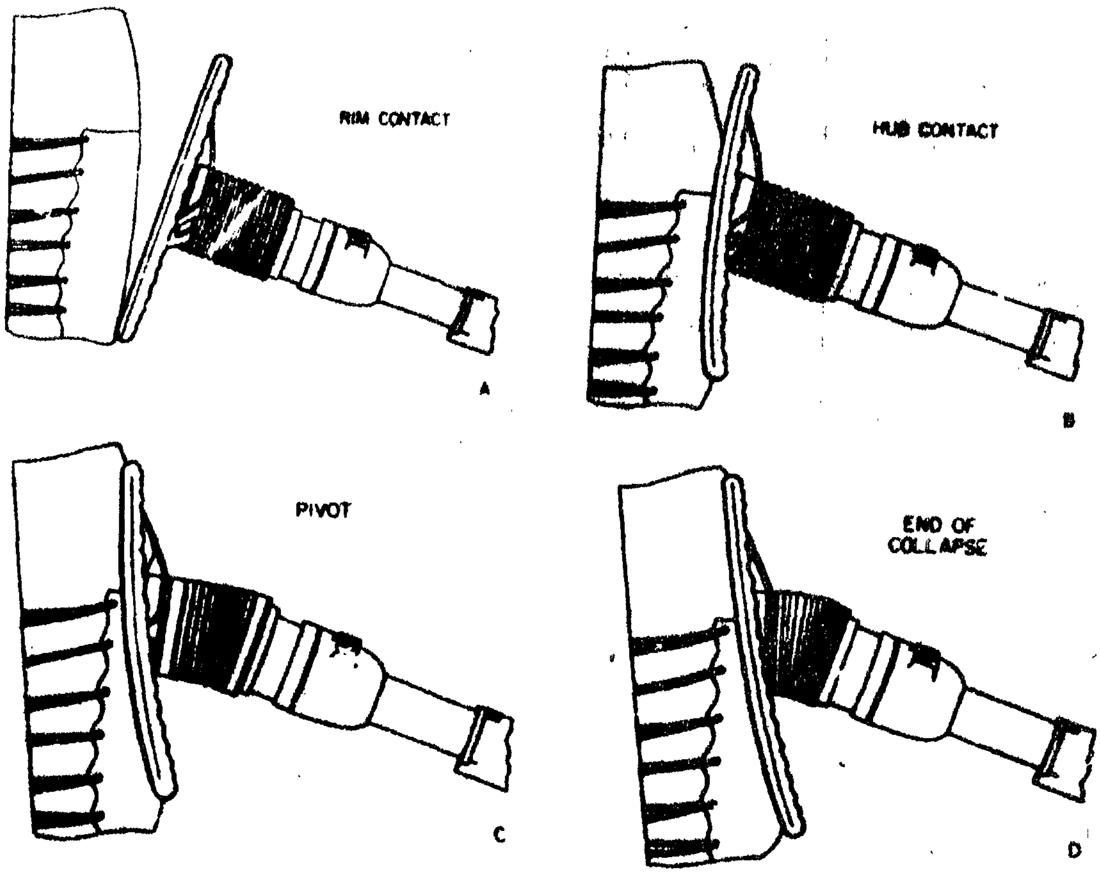


Bottom View of Shear Capsule

FIGURE 3-19: Close-up of shear capsule and bracket mounting. The bottom view clearly shows how the shear capsule is designed to prevent rearward column intrusion but allow forward compression by occupant loading [47].

FIGURE 3-20: The engine-compartment telescoping device (E) and the long thin flexible shaft to the forward-mounted steering gearbox (D) are effective in preventing steering column intrusion in severe frontal crashes. The forward-mounted gearbox allows the steering column angle to be closer to horizontal [72].

FIGURE 3-21: The Steering Wheel Energy Absorbing Device is designed to effectively collapse even in cases of non-axial loading by the occupant. These drawings were made from actual laboratory test films. The canister initially deforms on one side until the occupant load is spread evenly over the wheel (C). Then it collapses to absorb the occupant load (D) [3].



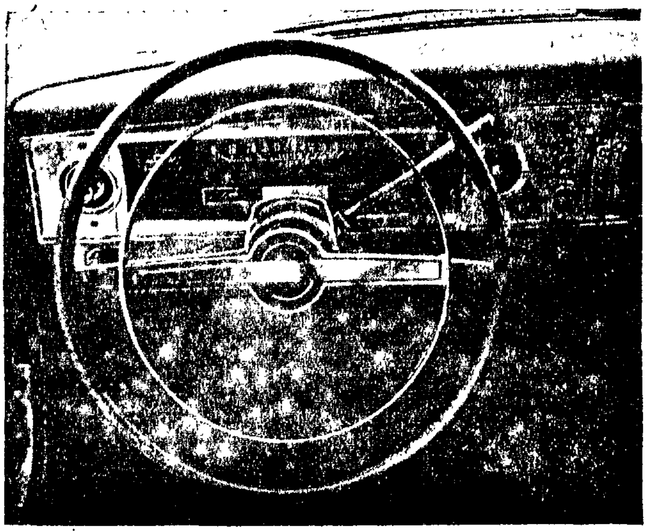


FIGURE 3-22: Pre-Standard steering wheel. Note: (1) small, rigid, hub, which bears occupant load in severe collisions, (2) narrow, brittle spokes and rim, (3) metal horn ring which may cause disfiguring injuries, (4) other metal trim and transmission selection indicator [12].

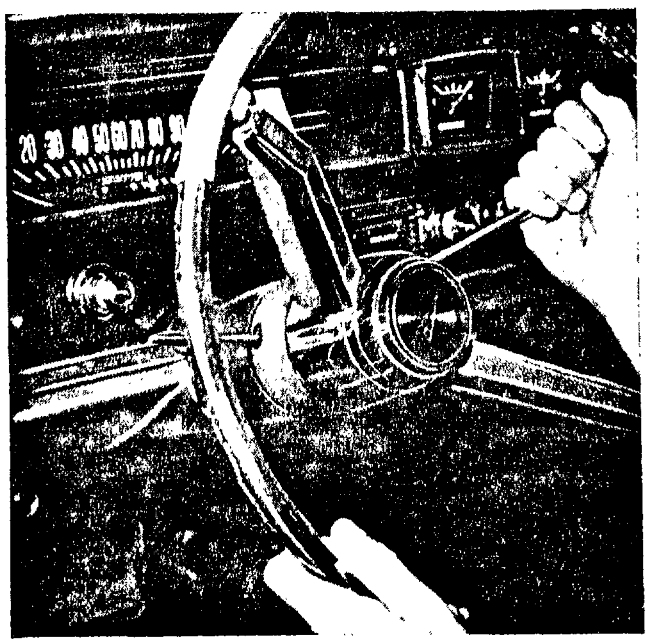


FIGURE 3-23: Steering wheel design 1 year before compliance. The horn ring is gone and the "deep dish" design may prevent hub contact in a low severity crash. But the narrow spokes and small hub provide little protection in severe crashes. There is extensive metal trim [13].

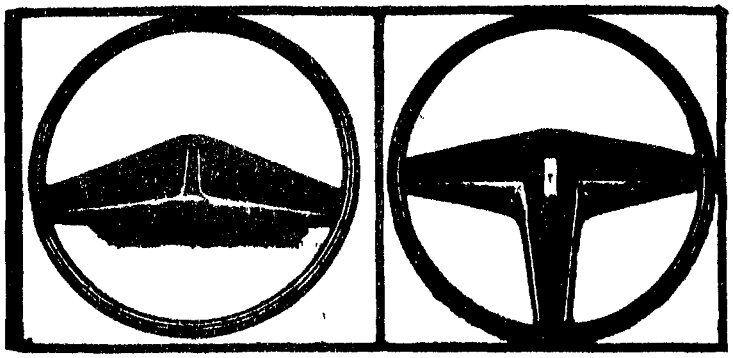


FIGURE 3-24: Post-Standard steering wheels. The hub and spokes present a broad, integral, padded energy-absorbing surface for occupant contact. The wide spokes and rim are strongly attached to one another. The post-Standard wheels are of smaller diameter and less likely to contact the face or abdomen [54].

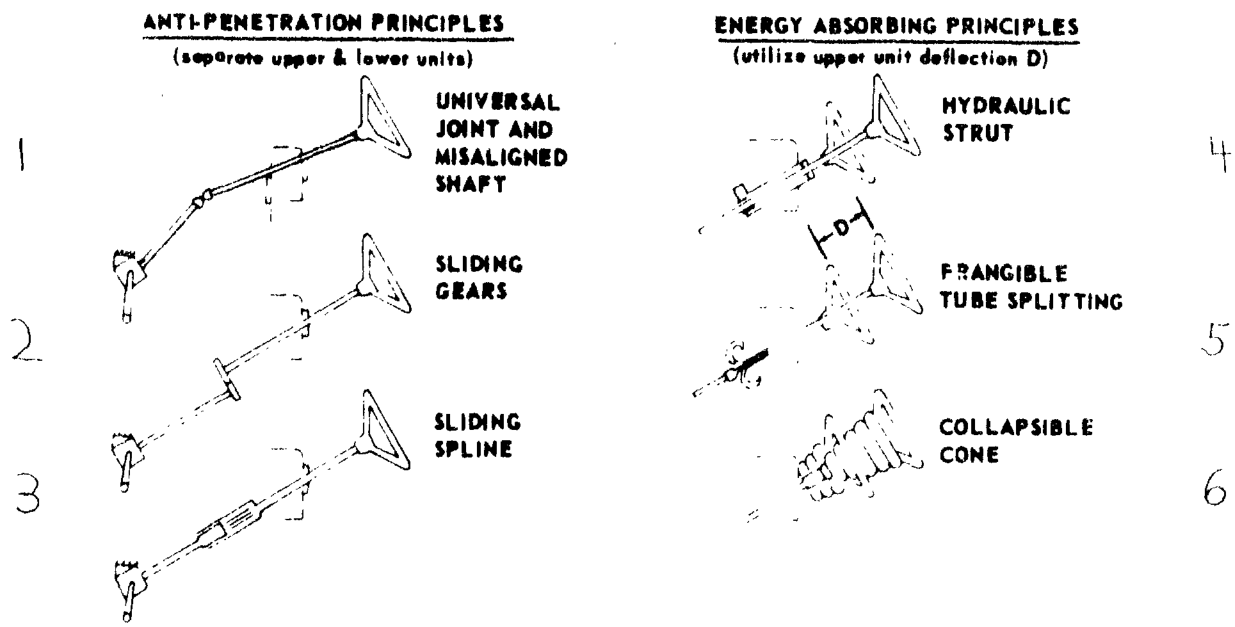


FIGURE 3-25: In 1964, R.A. Wolf suggested 6 concepts for a safer steering assembly. The concepts resemble: (1) the U-joints on recent Fiats and Volkswagens, (2) the forward mounted gearbox, (3) the customary engine compartment telescoping unit, (4) the ball or groove type tube, (5) the slotted jacket column and (6) the steering wheel EAD [75].

3.7.4 Successful post-Standard steering assembly performance

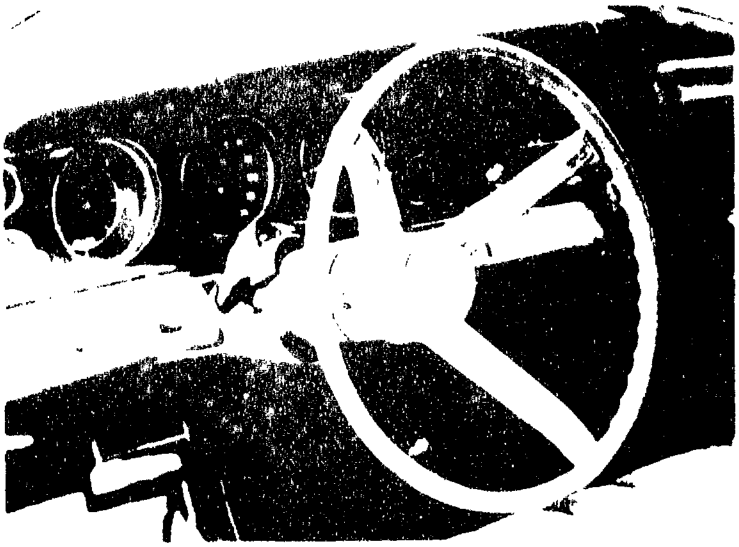
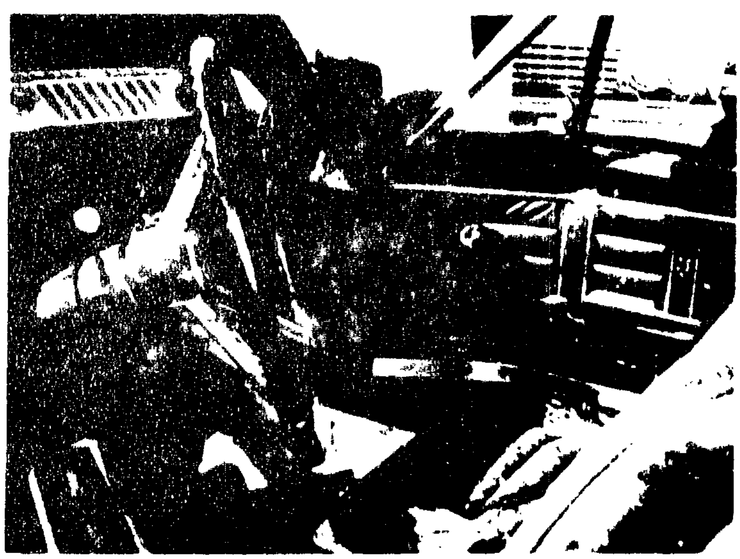


FIGURE 3-26: Completely successful functioning of the energy-absorbing column in a moderately severe frontal crash (1967 Chevrolet). The driver contact compressed the column 4 inches and resulted in no injury. The rim and spokes are intact, showing that the EA device carried the load [34].

FIGURE 3-27: Successful performance in a severe frontal impact (1967 Oldsmobile going 45-50 mph contacted trees). There were 4 inches of EA compression. The engine compartment device telescoped 5 3/4 inches and prevented intrusion. Note that the integrity of the rim and spokes was preserved. The driver did not sustain chest injury [34].



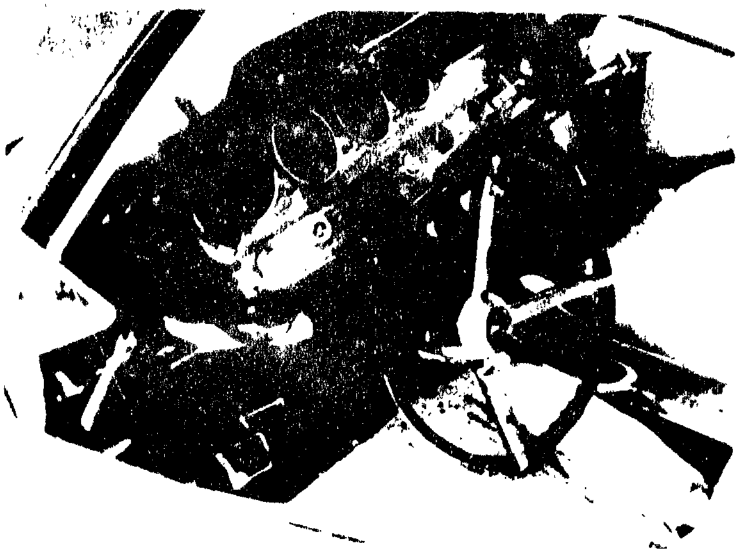
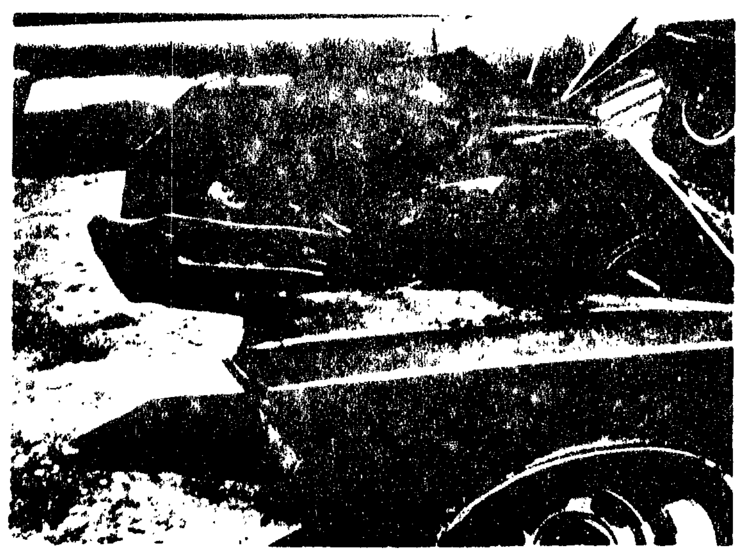


FIGURE 3-28: Dramatic performance of the steering assembly in an extremely severe frontal crash. This 1967 Pontiac GTO struck a tree while travelling 45-50 miles per hour. The crash damage caused severe intrusion of the instrument panel, but 8 inches of underhood telescoping prevented steering column intrusion. The mesh device collapsed 6 inches. Rim and spoke integrity was maintained. The steering wheel is now nearly flush with the instrument panel. The driver suffered one fractured rib [34].

FIGURE 3-29: Exterior damage to the 1967 Pontiac GTO pictured in Figure 3-28 [34].



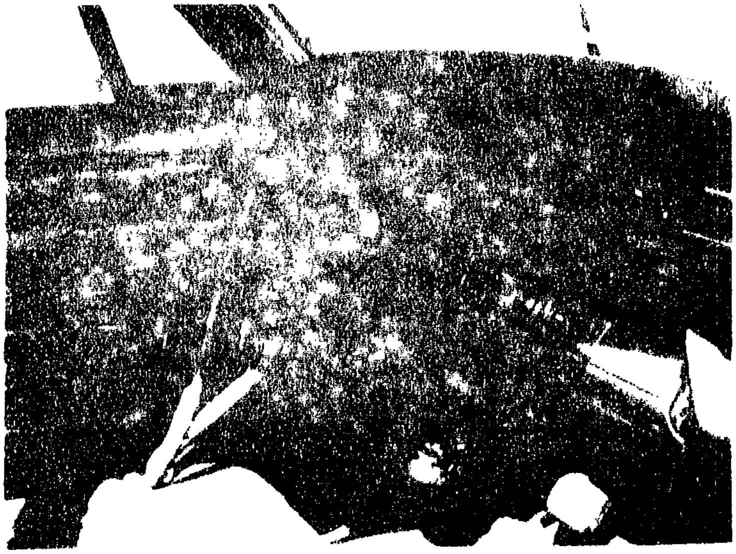


FIGURE 3-30: Crash damage that forces the column to tilt downwards is often associated with good EA device performance. This 1967 Chevrolet was involved in a 25 mph head-on collision. The column tilted downward but compressed 6 1/4 inches. The driver sustained minor injury [34].

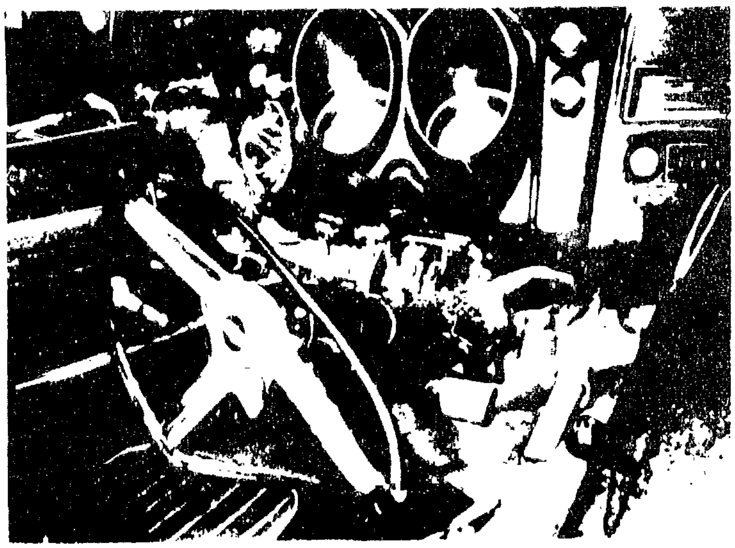


FIGURE 3-31: The column can perform well when it is tilted downwards, even in extremely severe crashes. In this 1968 Camaro, the column was completely stripped from the mounting bracket, yet it compressed 7 1/8 inches. Note that the rim and spokes maintained their integrity despite the severe loads they absorbed. What sort of abdominal injuries would this crash have produced in a pre-Standard car? [34].

FIGURE 3-32: The EA columns function especially well when the driver wears a lap belt, because it enhances axial loading. This 1967 Firebird sustained a Delta V of approximately 35 mph in a head-on collision with an Oldsmobile. The lap-belted driver compressed the column 5 inches and his chest was "mildly tender" after the crash [34].

3.7.5 Problems with post-Standard steering assembly performance

FIGURE 3-33: The Standards sometimes allow substantial upward column intrusion, especially when crash damage is low on the car. Upward tilting is often associated with binding of the column - i.e., failure of the EA device to compress under load [28].

FIGURE 3-34: A lateral force component (PDOF = 11 or 1) is often associated with binding of the column and sideways tilting. In this crash (PDOF = 11), the EA device did not compress and the steering wheel failed under non-axial load [28].

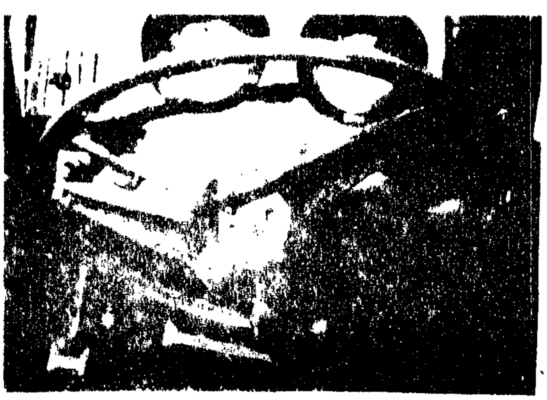
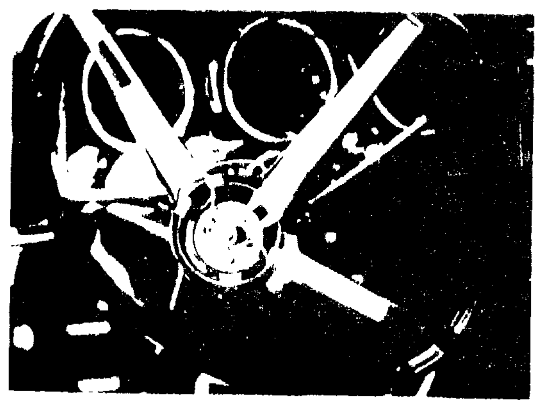


FIGURE 3-35: The gross failure of the steering wheel spokes in this tree impact with Delta V = 32 mph led to critical abdominal injury [65].

FIGURE 3-36: The failure of the lower spoke caused serious abdominal injury [28].

FIGURE 3-37: The thin metal spokes of this optional "sporty" steering wheel yielded under load. Forces were concentrated on the hub - resulting in fatal chest injury [65].



CHAPTER 4

THE COST OF STANDARDS 203 AND 204

4.1 Objective

One of the goals of this evaluation is to estimate the actual cost of Standards 203 and 204, in order to allow a fair comparison of actual benefits and costs.

The "cost of Standards 203 and 204" is defined as the net increase, due to these Standards, in the lifetime cost of owning and operating an automobile. There are 3 principal sources of increased cost: (1) Equipment installed in order to meet the compliance tests. (2) Voluntary improvements in the crashworthiness of steering assemblies (not strictly required to meet compliance tests). (3) The weight of materials and equipment added, which increases lifetime fuel consumption. The cost of the voluntary improvements, as well as their benefits, have been attributed to Standards 203 and 204 throughout the evaluation (see Sections 1.2 and 3.4.3).

Benefits were estimated for the baseline year 1978 (see Section 2.2). Therefore, costs will be estimated in 1978 dollars.

During the baseline year 1978, there were post-Standard cars of model years 1967-79 on the highways. The benefits were estimated using an accident data file which contained a mix of post-Standard cars from model years 1967-79 and a mix of post-Standard steering assembly types representative of all of those model years. For example, even though the mesh type column was no longer produced in 1978, it is well represented in 1978 accident data (i.e., by cars produced in 1967-73 and involved in crashes in 1978). Thus, when benefits are calculated for base year 1978, using 1978 accident data, the mesh type column contributes substantially to the total benefits.

By the same logic, the cost of Standards 203 and 204 for the base year 1978 is the average cost for vehicles on the road in 1978, which include a representative mix of 1967-79 post-Standard cars. It is not the average cost for vehicles produced in 1978.

4.2 Procedure for estimating costs

A procedure has been developed for estimating the cost and weight of equipment changes in response to NHTSA standards [51]. It was used for estimating the cost of Standards 203 and 204 [52]. The procedure is based on component cost estimating techniques that are widely used in the automotive industry.

The vehicle systems relevant to the Standard are acquired, torn down and examined for a representative sample of post-Standard cars and for corresponding pre-Standard cars. In the case of Standards 203 and 204, the steering assemblies and front structures were examined. The weights, materials, processing and finishing of individual components and the assembly method are established. The type, rough weight and finished weight of material is determined for each detail part, as well as the processing and assembly labor required, the scrap rate, machines and tooling utilized, the production quantity and the amortization period.

These data are used to calculate materials cost, labor cost, tooling, assembly and variable burden. Thus a variable cost and weight is estimated for each post-Standard steering assembly in the sample. The cost and weight is separately estimated for each corresponding pre-Standard steering assembly.

Manufacturer's fixed and nonvariable costs and dealer's markups are added to the variable cost to obtain an estimate of the consumer price.

The cost of a specific post-Standard model's steering assembly, minus the cost of the corresponding pre-Standard model's steering assembly, equals the incremental consumer cost of steering assembly changes made in that model in response to Standards 203 and 204. The incremental weight is similarly obtained.

Four vehicle subsystems were examined for possible modifications in response to Standards 203 and 204. Three of them were subsystems of the steering assembly: (1) The main steering column assembly, including the steering shaft, shift tube, jacket, energy absorbing and telescoping devices and mounting brackets. (2) The intermediate shaft between the steering gearbox and the steering column. (3) The steering wheel and spokes. (See Section 3.4.3.)

The fourth subsystem studied was the front structure of the vehicle. It was deemed possible that structural changes were made in order to reduce the likelihood of column intrusion (Standard 204). Seven post-Standard front structures and 5 corresponding pre-Standard structures were examined. Since the post-Standard structures were, in all cases, virtually identical to their pre-Standard counterparts, it was concluded that no structural changes were made in response to Standard 204 [52]. This finding is consistent with the literature on Standards 203 and 204, which makes no mention of structural changes (see Section 3.4.3).

Table 4-1 shows that cost and weight estimates were made for 14 post-Standard steering column assemblies. The cost estimates were made in <u>1979</u> dollars. The 4 estimates below the line in Table 4-1 were not used in estimating the

TABLE 4-1

GROSS COST AND WEIGHT ESTIMATES FOR 14 POST-STANDARD STEERING COLUMN ASSEMBLIES AND CORRESPONDING PRE-STANDARD STEERING COLUMN ASSEMBLIES [52]
(1979 dollars)

Post-Standard Model				Corresponding Pre-Standard Model		
Make/Model	Device	Total Cost	Total Weight	Make/Model	Total Cost	Total Weight
67 Plymouth Valiant	Mesh	$21.69	12.36 lbs.	66 Plymouth Valiant	$ 9.61	10.23 lbs.
67 Chevrolet Chevelle	Mesh	24.17	12.79	66 Chevrolet Chevelle	12.05	11.25
67 Chevrolet Impala	Mesh	18.06	10.92	66 Chevrolet Impala	10.49	9.81
70 Chevrolet Chevelle	Ball	18.35	11.27	66 Chevrolet Chevelle	12.05	11.25
69 Chevrolet Impala	Ball	18.99	11.91	66 Chevrolet Impala	10.49	9.81
68 Ford Galaxie	Slotted	18.06	9.56	66 Ford Galaxie	10.87	9.36
70 Ford Galaxie	Slotted	19.15	11.75	66 Ford Galaxie	10.87	9.36
73 Ford Torino	Grooved	19.42	9.74	66 Ford Fairlane	10.36	9.21
76 Plymouth Valiant	Slotted/Mandrel	20.58	10.85	66 Plymouth Valiant	9.61	10.23
70 Dodge Challenger	Wheel Canister	19.27	11.75	66 Plymouth Valiant	9.61	10.23
68 Volkswagen Beetle	Mesh	24.05	7.77	66 Volkswagen Beetle	21.17	4.83
67 AMC Rambler	Mesh	23.21	12.29	-		
70 AMC Rambler	Ball	24.19	13.56	-		
68 Toyota Corona	Mesh	15.44	6.89			

average cost of Standards 203 and 204: for 3 of the models, there was no corresponding pre-Standard model of the same manufacturer, so the cost and weight added by the Standards could not be accurately estimated. The 1968 Volkswagen Beetle was also discarded because it used a simple mesh design that was soon modified and was not a "typical" mesh-type column (although it had the lowest incremental cost - $2.88 - of any of the columns examined).

The 10 cars above the line in Table 4-1 provide adequate information for estimating the average cost and weight added to steering column assemblies by Standards 203 and 204. All 6 major energy absorbing device types are represented, as are the 3 largest U.S. auto manufacturers. Moreover, there are multiple data points for the 3 most common energy absorbing device types (mesh, ball and slotted columns).

Table 4-2 shows the cost and weight added by Standards 203 and 204 to the 10 post-Standard steering columns. The estimates are obtained by subtracting the gross cost and weight of the corresponding pre-Standard columns (right side of Table 4-1) from the gross cost and weight of the post-Standard columns (left side of Table 4-1).

The steering column with the lowest incremental cost was the ball-type 1970 Chevelle ($6.30). The mesh type 1967 Chevelle had the highest added cost ($12.12). The Standards added negligible weight to the cars, ranging from 0.02 pounds for the 1970 Chevelle to 2.39 pounds for the 1970 Galaxie.

The cost and weight estimates reflect the actual observed differences between pre- and post-Standard steering columns. Some of the differences may be

TABLE 4-2

COST AND WEIGHT ADDED BY STANDARDS 203 AND 204
TO STEERING COLUMN ASSEMBLIES
(1979 dollars)

			Standard 203/204 Added:	
	Make/Model	Device Type	Cost	Weight
67	Plymouth Valiant	Mesh	$12.08	2.13 lbs.
67	Chevrolet Chevelle	Mesh	12.12	1.54
67	Chevrolet Impala	Mesh	7.57	1.11
	AVERAGE:	MESH	10.59	1.59
70	Chevrolet Chevelle	Ball	6.30	0.02
69	Chevrolet Impala	Ball	8.50	2.10
	AVERAGE:	BALL	7.40	1.06
68	Ford Galaxie	Slotted	7.19	0.20
70	Ford Galaxie	Slotted	8.28	2.39
	AVERAGE:	SLOTTED	7.74	1.30
73	Ford Torino	Grooved	9.06	0.53
76	Plymouth Valiant	Slotted/Mandrel	10.97	0.62
70	Dodge Challenger	Wheel Canister	9.66	1.52

the result of changes in the length or layout of the steering column necessitated by car design or styling changes and may not be directly related to Standards 203 and 204. Thus, some of the cost and weight variations from model to model, in Table 4-2, may not be directly related to the Standards.

The ball type column had the lowest average incremental cost ($7.40) and the slotted/mandrel type had the highest cost ($10.97). The grooved column added the least weight (0.53 pounds) and the mesh type added the most (1.59 pounds).

Obviously, no single device type stands apart from the others in terms of cost and weight. Moreover, the small variations of average cost and weight from one device type to another may, to some extent, be due to variation among the individual makes and models used in computing the averages.

The evaluation objective was to calculate the average incremental cost and weight for cars on the road in 1978. The distribution of the 6 major energy absorbing column types in cars on the road during 1978 should be similar to their distribution in National Crash Severity Study cases, since the data were collected during 1977-79 (see Table 6-8). The average incremental cost and weight of post-Standard steering columns can be estimated by taking the weighted average over the 6 major column types, using the NCSS distribution of column types as the weight factors. The calculation is performed in Table 4-3.

Standards 203 and 204 increased the cost of steering column assemblies by an average of $8.41 (in 1979 dollars) per car and added an average of 1.11 pounds.

TABLE 4-3

AVERAGE COST AND WEIGHT ADDED TO CARS ON THE ROAD IN 1978 BY STANDARD 203 AND 204 STEERING COLUMN ASSEMBLIES

(1979 dollars)

Steering Column Type	Average Cost	Average Weight	N of NCSS Cases
Mesh	$10.59	1.59	4542
Ball	7.40	1.06	13,511
Slotted	7.74	1.30	4,311
Grooved	9.06	0.53	3,528
Slotted/mandrel	10.97	0.62	1,355
Wheel canister	9.66	1.52	844
WEIGHTED AVERAGE	$8.41	1.11 pounds	

TABLE 4-4

AVERAGE COST PER CAR FOR STANDARDS 203 AND 204

	Cost Item	1978$	1979$	1980$
1.	Steering column changes			
	a. Cost	7.86	8.41	
	b. Weight (1.11 lbs. @ 1.1 gallons/lb.)	1.26		1.53
2.	Intermediate shaft changes	1.01	1.08	
3.	Steering wheel improvements	.33	.35	
	TOTAL	$10.46		
	(1978 dollars)			

An intermediate shaft is used between the steering column assembly and the steering gearbox in some cars with a forward-mounted steering gearbox. The engine compartment telescoping device, which was installed for the purpose of complying with Standard 204, was sometimes located on the intermediate shaft.

Telescoping post-Standard and rigid pre-Standard intermediate shafts were examined. The post-Standard shaft was found to cost $2.75 more (in 1979 dollars) and weigh about the same as the pre-Standard design. This device is used in about 39 percent of all passenger cars, so the average cost per car is $1.08 (in 1979 dollars) [52].

The voluntary improvements to steering wheels and spokes included increasing the number of spokes, making the rim and spokes stronger, padding the hub, removing the horn ring and metal trim and reducing the diameter of the wheel (See Section 3.4.3). The only change that measurably increased cost was increasing the number of spokes. Removal of horn rings and trim and reduction of wheel size led to reduced cost. Pre- and post-Standard steering wheels were examined and the cost increase was not found to exceed $0.35 (in 1979 dollars).

4.3 Average and total cost of Standards 203 and 204

The evaluation objective was to determine a single figure for the lifetime consumer cost of Standards 203 and 204, expressed in 1978 dollars. That figure is calculated in Table 4-4.

In the preceding section, 3 vehicle subsystems were found to have increased in cost as a result of Standards 203 and 204. The costs were expressed in

1979 dollars (see the middle column of Table 4-4). The cost of manufacturing the subsystems increased from 1978 to 1979 by approximately 7 percent [52]. The 1979 dollar costs are converted to 1978 dollars by dividing by 1.07. The 1978 dollar costs are shown in the first column of Table 4-4.

The Standards were found to add 1.11 pounds to the weight of the steering column assembly. Each incremental pound of weight added to a car results in the consumption of an average of 1.1 additional gallons of fuel over the lifetime of the car [16]. The average mid-1980 price of fuel was $1.25 per gallon. Based on this value, the lifetime consumer cost for weight added by the Standards is:

1.11 pounds x 1.1 gallons/pound x $1.25 = $1.53 (in 1980 dollars)

The overall cost of automotive transportation increased by an average of approximately 10 percent a year during the late 1970's [2]. The 1980 dollar costs can be converted to 1978 dollars by dividing by 1.21. The 1978 dollar cost - $1.26 - is shown in the first column of Table 4-4.

Table 4-4 shows that the total consumer cost of Standards 203 and 204 (in 1978 dollars) averaged $10.46 per car, for passenger cars on the road in 1978. The cost includes $8.87 for equipment changes required to meet the compliance tests ($7.86 for the steering column plus $1.01 for the intermediate shaft), $1.26 for lifetime fuel consumption due to added weight, and $0.33 for voluntary improvements to the steering wheel and spokes.

The estimate of $10.46 per car, based on detailed examination of pre- and post-Standard vehicles, is lower than the cost estimate of $17 (in 1974 dollars) contained in the General Accounting Office's report on the <u>Effectiveness, Benefits</u>

and Costs of Federal Safety Standards for Protection of Passenger Car Occupants [17]. Their estimate was based on an average of quotations supplied by the vehicle manufacturers.

Since about 10 million passenger cars are sold annually in the United States, the cost of Standards 203 and 204 is about $ 105 million per year.

CHAPTER 5

THE OVERALL EFFECTIVENESS OF STANDARDS 203 AND 204

There is definitive evidence that Standards 203 and 204 have reduced, by about 35 percent, the incidence of drivers being injured by steering assembly contact during a frontal crash in a passenger car. Because about 40 percent of the fatal or serious driver injuries in frontal crashes are primarily the result of steering assembly contact, the Standards have reduced, by about 15 percent, the drivers' risk of fatal or serious injury in a frontal crash. The basis for these findings is presented in this chapter. It begins with a review of previous effectiveness studies - based on investigator-collected and State data files. Next, the analyses conducted for this evaluation are described. The first is based on the investigator-collected National Crash Severity Study (NCSS). The other one used the Fatal Accident Reporting System (FARS), which is derived from State data. The chapter concludes with an analysis of cost-effectiveness and a brief summary comparison of the effectiveness studies.

This chapter is concerned with how effective the Standards are; the question of why they are effective is the subject of Chapter 6.

5.1 Review of previous effectiveness studies

Findings from existing statistical studies are close to unanimous in ascribing substantial benefits to Standards 203 and 204. There were consistent effectiveness results in 6 of the 7 studies that are reviewed below. The first 3 of them were based on investigator-collected or in-depth data and specifically measured steering assembly contact injury reduction. The second group of 3 were based on State data and measured overall driver injury reduction. Only the 7th study contains a finding of no effectiveness - although it appears this result is due to biases in the data.

5.1.1 Studies based on investigator-collected data

Lundstrom and Cichowski [45] of General Motors analyzed Automotive Crash Injury Research (ACIR) data and found significant benefits for Standards 203 and 204. ACIR was in many ways the predecessor of the National Crash Severity Study and the National Accident Sampling System. 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 fairly uniform sample of injury-producing accidents involving then recent American vehicles. The ACIR program lasted from 1953 to 1969 and made a large contribution to safety research and rulemaking.

Lundstrom and Cichowski looked at the source of driver injuries in GM cars with frontal impacts and compared rates for pre-Standard (1964-66) and post-Standard (1967-68) cars. The rates are shown in Table 5-1. They found a statistically significant 32 percent reduction in torso injury involving steering assembly contact and a significant 27 percent reduction in head and facial steering assembly injury. For comparison and control, they checked head injury rates from other sources and found no significant change.

TABLE 5-1

ACIR INJURY RATES FOR DRIVERS OF GM CARS
INVOLVED IN FRONTAL CRASHES
(Lundstrom & Cichowski, 1969)

	Pre-Standard (1964-66)	Post-Standard (1967-68)
N of cases	1500	148
Torso injury from steering assembly	31%	21%*
Head injury from steering assembly	26%	19% *
Head injury from any source	68%	70%

*significant reduction for post-Standard cars

Nahum, Siegel and Brooks [56] analyzed Multidisciplinary Accident Investigation (MDAI) data collected in the Los Angeles area during 1962-69. The data were a non-probability sample of passenger car crashes in which

(1) at least one occupant suffered AIS ≥ 2

(2) at least one occupant survived

(3) at least one occupant was not ejected

These criteria complicate the interpretation of injury rates. An inspection of their data shows a higher percentage of frontal impacts among the older cars: Since steering assembly contact occurs primarily in frontal impacts, this would exaggerate the steering assembly injury rates in the older cars. It appears that the most satisfactory way to interpret their data is to compare the AIS ≥ 2 steering assembly injury rates to the injury rates for contact with other components in front of the driver (instrument panel, windshield, etc.) The comparative rates are shown in Table 5-2.

TABLE 5-2

UCLA MDAI DRIVER AIS ≥ 2 INJURY RATES DUE TO
STEERING ASSEMBLY VERSUS OTHER FRONTAL CONTACT POINTS
(Nahum, Siegel & Brooks, 1970)

	MY 1960-66	MY 1967-68
N of drivers	178	328
Percent with AIS ≥ 2 steering assembly injury	46	14
Percent with AIS ≥ 2 other frontal contact injury	41	27

The reduction in the rate of steering assembly contact injury was a statistically significant 54 percent greater than the reduction in other types of frontal contact injury.

O'Day and Creswell [62] analyzed MDAI data from the University of Michigan and UCLA in 1971. They restricted their attention to drivers in frontal impacts with

(1) known chest contact with the steering assembly

(2) impact speed at least 25 mph.

The purpose of such specific selection criteria was to make the pre- and post-Standard cases as closely comparable as possible - i.e. to minimize possible confounding from the non-probability case selection methods used in the MDAI program.

The injury rates for the pre- and post-Standard cars are presented in Table 5-3. O'Day and Creswell found a statistically significant 45 percent reduction in AIS $\geq$ 3 injury for post-Standard cars, with similar statistically significant reductions at the AIS $\geq$ 4 and fatal levels.

TABLE 5-3

MDAI INJURY RATES FOR DRIVERS IN SEVERE FRONTAL CRASHES WITH STEERING ASSEMBLY CHEST CONTACT (O'Day & Creswell, 1971)

	Pre-Standard	Post-Standard
N of cases	57	262
Fatal injury	19%	10%*
AIS $\geq$ 4 injury	35%	21%*
AIS $\geq$ 3 injury	56%	31%*

* Significant reduction for post-Standard cars.

5.1.2 Studies based on State data

Since police do not normally record the injury-causing contact points, State data cannot be used to estimate the reduction in steering assembly contact injury, but only the reduction in overall injury. Steering assembly contact is primarily responsible for about 46 percent of severe driver injury in frontal crashes (see Table 3.2). Thus, the overall injury reduction is expected to be about 46 percent as large as the steering assembly injury reduction – *e.g.* a 15 percent reduction in the former is consistent with a 33 percent reduction in the latter. In view of this point, the results of 3 State studies that follow are quite compatible with the 3 studies summarized in the preceding section.

In 1971, Levine & Campbell analyzed North Carolina data from calendar years 1966 and 1968 [44]. They compared fatal and serious (K + A) injury rates with and without Standards 203 and 204 for unrestrained drivers in frontal impacts with another car. The injury rates are shown in Table 5-4.

TABLE 5-4

NORTH CAROLINA INJURY RATES IN 1966 AND 1968
UNRESTRAINED DRIVERS IN FRONTAL CAR-TO-CAR IMPACTS
(Levine & Campbell, 1971)

	Pre-Standard (1964 -)	Post-Standard (- 1968)
N of drivers in frontal car-to-car impacts	12,039	5,635
Percent with K + A injury	10.3	8.8*

* Significant reduction for post-Standard cars

Levine and Campbell found a statistically significant 14 percent reduction in the K + A injury rate in the car-to-car frontals. They obtained similar reductions when they compared restrained drivers of pre- and post-Standard vehicles. They did not find any reductions in minor injury.

In 1974, A.J. McLean [50] also analyzed data from North Carolina. He used the files for calendar year 1971-72, looking at frontally damaged model year 1965-72 cars involved in front-to-front or front-to-rear car-to-car crashes. (He felt that in these crashes the driver would be somewhat more likely to move straight ahead into the steering assembly than in other types of frontal impacts.) Although McLean relied on the same State as Campbell & Levine, it should be noted that he worked with entirely different calendar year files and somewhat different model years and crash types.

McLean's K + A injury rates for unrestrained drivers are displayed in Table 5-5. He found a statistically significant 20 percent reduction in the injury rate for post-Standard cars.

TABLE 5-5

NORTH CAROLINA INJURY RATES IN 1971-72 FOR UNRESTRAINED DRIVERS IN FRONT-TO-FRONT OR FRONT-TO-REAR COLLISIONS WITH A PASSENGER CAR
(McLean, 1974)

	Pre-Standard* (1965-66)	Post-Standard (- 1972)
N of cases	1862	3626
K+A injury rate	10%	8% **

* Excluding 1967 Fords with padded hubs
** Significant reduction for post-Standard cars

The New York State Department of Motor Vehicles published a study of the Standard's effectiveness in 1973 [58]. It was based on their 1968 and 1969 data files. It was limited to head-on car-to-car collisions - an especially severe accident category. Injury rates (K+A) were calculated for drivers of cars one model year before the Standards and for the first model year that complied with the Standards. The rates are shown in Table 5-6.

TABLE 5-6

NEW YORK STATE INJURY RATES IN 1968-69 FOR DRIVERS IN HEAD-ON CAR-TO-CAR CRASHES

	Last Pre-Standard Model Year	First Post-Standard Model Year
N of cases	1793	1603
K + A injury rate	12.1%	9.2%*

* Significant reduction for post-Standard cars

There was a statistically significant 24 percent K+A injury reduction for the post-Standard cars in head-on crashes.

5.1.3 Studies that may contain major biases

In 1974, T.E. Anderson published an analysis [5] which indicated little or no effectiveness for the Standards in preventing steering assembly contact injury. The study used ACIR data from 1960-65 to derive the pre-Standard injury rates. It used primarily Calspan Level 3 data from 1968-73, plus some ACIR data, for the post-Standard rates. Thus, injury rates from essentially 2 different data files are compared. The files are outwardly similar non-probability samples of injury accidents. It is likely, though that Calspan Level 3 tended to result in the sampling of higher-injury accidents than ACIR, even after controlling for other conditions. Since the drivers of post-Standard cars were primarily found in the former and the pre-Standard car drivers exclusively in the latter, it is possible that the post-Standard injury rate was biased upward by an amount that cancels the actual benefit of the Standards. The principal evidence that confirms the presence of a bias is:

(1) Anderson published another study [4], using the same methodology, in which lap-belted occupants had higher injury rates than unrestrained occupants - i.e., anomalous results were obtained for a safety device of proven effectiveness.

(2) Lundstrom and Cichowski's study, based on ACIR data alone, showed significant benefits for Standards 203 and 204. So did O'Day and Creswell's study of MDAI data alone. Their data resembled Calspan Level 3. (See Section 5.1.1)

In a somewhat similar vein, Gloyns and Mackay's studies [29], [30] claimed that the steering wheel EAD is far more effective than the steering column EAD (see Section 6.2.1). They could be interpreted as suggesting that the latter - which is used in 99% of American cars - is probably ineffective and possibly dangerous. Their data, however, consisted of a relatively small sample of the two types of post-Standard cars and no pre-Standard cars at all. It does not appear a satisfactory basis for conclusions about the effectiveness of the steering column EAD versus the pre-Standard cars.

Although neither Anderson's nor Gloyns' reports should be relied on for a measurement of the overall effectiveness of Standards 203 and 204, they have stimulated research to find ways of enhancing the benefits of these Standards.

5.2 Analysis of National Crash Severity Study data

Since 1977, the National Crash Severity Study (NCSS) has been NHTSA's primary source of detailed information on vehicle and injury performance in highway accidents involving passenger cars. The analysis of this large file is a major component of the evaluation. After a description of the NCSS file, this section provides motivation and explanation of the principal measure of effectiveness that will be used with NCSS data: reduction of hospitalizing steering assembly contact injury. Next, there is a tabulation of the principal findings, viz., that the effectiveness of the Standards is 38 percent and that this corresponds to the prevention of 24,200 hospitalizing injuries annually. This is followed by an exposition of the modeling techniques used to control for potential confounding factors and obtain the principal estimate. Finally, there is an explanation of the error measurement methods used to obtain a confidence interval for this estimate, viz., 28 percent to 48 percent.

5.2.1 Description of the NCSS data

Seven multidisciplinary accident investigation teams under contract to NHTSA are collecting the NCSS data. The geographical areas in which they work were chosen by NHTSA to represent the United States as a whole. They have almost the same distribution of central city, suburban, small-town and rural population as the nation; there is at least one NCSS team in each of the nation's 4 demographic regions. Each team selects accidents for investigation within its area according to a strict probability sampling scheme. The sampling frame includes all police-reported "automobile towaway accidents" - i.e., crashes in which at least one passenger car was towed from the scene due to crash damage and in which a police officer filed an accident report. Specially trained NCSS investigators supplement the police accident report with theirown investigations of vehicle exterior and interior damage, injury information from medical records, driver interviews, inspection of the crash site, and computer reconstruction of accident speeds using the CRASH program [49]. General information about NCSS may be found in [39], specific investigations on NCSS representativeness in [64], and general-purpose tabulations of NCSS data in [69].

The version of the NCSS data used here is the one that became available on November 16, 1979. It included a total of 11,840 individual accident investigations, of which 6683 used the pre-April 1978 data elements and 5157, the somewhat different post-March 1978 data elements. These accidents included a total of just over 17,000 "case" vehicles, most but not all of which were towed passenger cars. For the purpose of this evaluation, a certain amount of data manipulation was required to put the "pre-April" and "post-March" files in a common format and eliminate unneeded data elements and "case" vehicles. The derivation of the file used for this evaluation is covered in Appendix A.

The NCSS file was completed in April 1980. The final file was not available for computer access by NHTSA offices until November 1980, which was 4 months after the analyses for this report had been completed. The final file contains 12,050 accidents, an increase of just 210 over the file used for this study. On the other hand, the National Accident Sampling System [46], which has replaced NCSS, will in the future provide compatible data. Thus, data collection for the purpose of this evaluation will continue indefinitely. In practice, though, the statistical precision of the estimates would not benefit much from further data collection. The pre-Standard cars are already outnumbered 8 to 1 on NCSS by the post-Standard cars - i.e., only an increase in the pre-Standard sample size would substantially improve precision. But since the youngest pre-Standard cars are now 13 years old, they will account for an ever-diminishing proportion of the accident population.

The specific data elements on the NCSS file that are relevant to the evaluation of Standards 203 and 204 are the following:

(1) Accident configuration and number of vehicles involved

(2) Case vehicle information: make, model, model year and weight

(3) Case vehicle Collision Deformation Classification [11]:

a. Principal direction of force

b. General area of damage

c. Specific horizontal and vertical damage location

(4) Type of vehicle or object contacted

(5) Delta V - velocity change during contact

(6) Magnitude and direction of steering column intrusion

(7) Driver age, sex and belt usage

(8) Type of treatment required by driver

(9) Driver injury information

a. contact point

b. body region and lesion

c. severity (AIS) [1].

NCSS is the first study that employs probability sampling methods and contains these variables.

There are 2 factors that complicate the use of NCSS data for the evaluation and influence the choice of a measure of effectiveness:

- incidence of unknown or missing data on key variables
- unequal sampling proportions.

The variables for which the missing data rate is relatively high are the Collision Deformation Classification (20%), Delta V (50%), Overall AIS (20%), Occupant Contact Point (30%), and Belt Usage (15%).

Knowledge of the vehicles' Collision Deformation Classification is important for the evaluation, since it is intended to restrict the study to "frontal" crashes. Without the CDC, it is difficult to judge if a NCSS vehicle was frontally impacted. Also, when the CDC is missing, it means that there has been no vehicle investigation, so Delta V and contact points will usually be unknown. It was decided to exclude cases with missing CDC's from the evaluation.

Although Delta V is missing on 50 percent of the full NCSS file, it is missing on only 30 percent of the cases with known CDC and frontal damage or force. Since Delta V is only used as a control variable (see Section 5.2.2), this is a tolerable unknown rate. Cases with unknown Delta V were not excluded. When Delta V is used as a control and its range of values grouped into categories, a separate category is assigned for unknown Delta V. Since the modeling process (Section 5.2.4) did not result in the selection of Delta V as an important control variable, the high unknown rate did not severely encumber this evaluation.

The missing data rate of 20 percent for overall AIS is, in a sense, an understatement. Since half of the occupants were known to be uninjured, it means that 40 percent of the injured occupants had unknown AIS. Many of these cases, but by no means all of them, were persons with apparent minor injury for whom no record of diagnosis or treatment was available. In order to use NCSS data for estimates of total numbers of casualties - i.e., the size of the problem - it is necessary to distribute the unknowns among AIS categories on the basis of other variables, such as type of treatment and police injury code (see Appendix A).

For estimating effectiveness of Standards 203 and 204, on the other hand, nothing needs to be done about cases with missing AIS: effectiveness will be measured in terms of steering assembly contact injury reduction (see 5.2.2). In other words, it is necessary to know the driver's contact point. The AIS is known in 97 percent of the cases in which the contact point is known.

The 30 percent missing data rate for injury-causing contact points is a serious problem. Since half of the occupants are uninjured, it means that the contact points are unknown for 60 percent of the injured occupants. Many of these are persons with apparent minor injury for whom no record of diagnosis or treatment was available. Nevertheless, even among drivers in frontal crashes requiring transport from the scene and overnight hospitalization, the contact point was unknown in 29.6 percent of the cases.

The most serious aspect of the problem, however, is that the missing contact point rates are significantly higher for pre-Standard 203/204 cars (34.6 percent of hospitalized drivers in frontal crashes) than in post-Standard cars (28.7 percent). Table 5-7 shows the distribution of known and unknown contact points.

TABLE 5-7

CONTACT POINT DATA AVAILABILITY BY STANDARD 203/204 COMPLIANCE
DRIVERS KILLED OR HOSPITALIZED IN FRONTAL CRASHES, NCSS

	Contact Points		Percent
	Known	Unknown	Unknown
Pre-Standard 203/204	214	113	34.6
Post-Standard 203/204	1404	566	28.7
Overall	1618	679	29.6

$\chi^2 = 4.57$ df = 1 $p < .05$

The effectiveness of Standards 203 and 204 will be measured as the reduction in the rate of steering assembly contact injury for post-Standard cars relative to pre-Standard cars (see Section 5.2.2). Injuries with "unknown" contact points are not counted in these rates. Among the injuries of "unknown" source, there are presumably some that were, in fact, caused by steering assembly contact. These should have been counted in computing the injury rates but were not, because of missing data on the contact point. Now, since the unknown contact point rate is higher for pre-Standard cars, there will presumably be more uncounted steering contact injuries for the pre-Standard cars than for the post-Standard cars. As a result, the Standards actually are more effective in reducing injuries than would have been estimated using only the cases with known contact points. In other words, the significantly different missing data rates on contact points in pre- and post-Standard cars create a bias which leads to an underestimate of the effect of the Standard. It is necessary to determine why the missing data rates are different and to develop analytic tools to remove the bias.

Discussions with NCSS project and team managers and statistical analyses of NCSS data made it clear that the difference in known contact points can be attributed entirely to a single factor: the NCSS teams. Table 5-8 shows that the teams with the highest missing data rates on contact points also by and large had the highest percentage of old cars.

TABLE 5-8

CONTACT POINT DATA AVAILABILITY AND PERCENT OF PRE-STANDARD CARS, BY TEAM, FRONTAL CRASHES, NCSS

Team	% of Fat./Hosp. Drivers With Unknown Contact Points	% of Cars Pre-Standard
Calspan	4	3.2
Highway Safety Research Institute	36	5.8
U of Indiana	39	9.0
U of Kentucky	13	10.9
U of Miami	40	10.3
Southwest Research Institute	29	15.2
Dynamic Science	67	22.1

The 2297 drivers on NCSS who were killed or hospitalized in frontal crashes were crosstabulated by the 3 variables, Standard 203/204 compliance (S), Contact point known-unknown (C), Team (T). A three-dimensional contingency table analysis suggested that

- Some teams had significantly more pre-Standard cars than others (Partial interaction term S x T had $\chi^2 = 83.26$, df = 6, $p < .0001$).

- Some teams had significantly higher missing data rates on contact points than others (Term C x T had $\chi^2 = 298.92$, df = 6, $p < .0001$).

- Team-by-team, there were no significant differences between the missing data rates for pre and post-Standard cars (Term S x C x T had $\chi^2 = 5.08$, df = 6, $p = .53$).

- When the data are standardized by team, there is no difference between the overall missing data rate for pre-Standard and post-Standard cars (Partial interaction term S x C had $\chi^2 < .01$, df = 1, $p = .98$).

The analysis shows that the difference in contact point missing data rates between pre- and post-Standard cars can be attributed entirely to team-to-team differences and that the resultant bias in measuring effectiveness can be removed by using "team" as one of the control (or standardization) variables in the modeling process of Section 5.2.4.

The detailed analyses of this report were completed by July 1980. Prior to then, it was known that some of the teams occasionally used an incorrect coding scheme for contact points during the first 7 months of 1977. The program to create the working file for the analyses included a transformation to correct the coding errors (Appendix A, Program No. 2).

In November 1980, when the final NCSS file became available for computer access, it was determined that the transformation did not correct all of the coding errors. Printouts of steering assembly contact injuries were obtained from the final NCSS file and from the working file used for this evaluation. There were 767 cases of steering assembly injury which appeared on both files, 15 injuries on the final NCSS which were coded nonsteering assembly injuries on the working file, and 11 nonsteering assembly injuries which were coded steering assembly injuries on the working file. Thus, the error rate on the working file is only (15 + 11)/(767 + 15) = 3%. The effectiveness of Standards 203 and 204 was also recalculated (without adjusting for confounding factors) using the final NCSS file (which contains corrected contact points plus 210 more accidents than the working file) and it was 1 percent lower than the corresponding statistic in the working file. This bias is much smaller than the 10 percent sampling error of effectiveness (see Section 5.2.3). The coding error problem is evidently not serious enough to justify redoing all of the detailed analyses of Chapters 3, 5 and 6 with the final NCSS file.

The 15 percent missing data rate for belt usage is reduced to just 2 percent by relying on driver-reported usage when the NCSS investigator **assesses** usage to be "unknown"and by relying on police-reported usage when neither driver nor investigator reported usage is available. This is the approach that was employed in the Restraint Systems Evaluation Project [38].

The NCSS investigators select which accidents are to be investigated by a rigorous probability sampling scheme. But NCSS is not a simple random sample. It is a stratified random sample, with 4 strata and unequal sampling proportions:

- 100% of accidents in which at least one towed car occupant is killed or transported from the scene and hospitalized overnight
- 25% of accidents in which at least one towed car occupant is transported from the scene (but no towed car occupant is killed or transported and hospitalized)

- 10% of other accidents involving towed passenger cars - except in Texas after March 1978

- 5% of other accidents involving towed passenger cars in Texas beginning April 1, 1978.

The objective of the stratified sampling with unequal proportions was to obtain substantially more precise estimates of injury and fatality rates than would have been possible from a simple random sample of the same size or cost. C.J. Kahane demonstrated in the evaluation of Standard 214 [37] that this objective could be achieved for AIS $\geq$ 2 and AIS $\geq$ 3 injury rates.

But an even greater gain in precision can be obtained by departing from the use of the AIS scale as the injury criterion. Consider, for example, the NCSS tabulation of sampling stratum by AIS shown in Table 5-9. Note that 808 of the 837 observed cases of AIS $\geq$ 3, or nearly 97 percent, occurred in the 100% sampling stratum. When the cases are properly weighted to produce unbiased estimates - i.e. when they are divided by the sampling fraction - the 100% stratum still accounts for 808/952, or 85 percent of the AIS $\geq$ 3 injuries. But when variances are calculated - a process typically requiring cases to be divided by the square of their sampling fraction - the contributions from 3 strata containing 15 percent of the injuries would exceed the contribution from the stratum that contains 85 percent of the injuries. Thus, the precision of any statistical inference about AIS $\geq$ 3 injury rates or reductions is greatly degraded by the uncertainty about a small subgroup pf the injuries. The harm is especially great when the injuries are categorized - say, by pre-post Standard, body region and PDOF. The single observation in Table 5-9 that is counted 20 times is destined to fall into one of the categories and make it appear much larger than it really is.

TABLE 5-9

OVERALL AIS BY SAMPLING STRATUM
NCSS DRIVERS IN FRONTAL CRASHES
(AIS 8 and 9 excluded)

Sampling Stratum	Unweighted Counts (Raw Data)	
	AIS ≥ 3	AIS < 3
100%	808	1828
25%	26	1508
10%	2	1593
5%	1	117
	Weighted Counts	
100%	808	1828
25%	104	6032
10%	20	15930
5%	20	2340

TABLE 5-10

TREATMENT/TRANSPORT BY SAMPLING STRATUM
NCSS DRIVERS IN FRONTAL CRASHES

Sampling Stratum	Unweighted Counts	
	Killed - or - Transported to Be Hospitalized	Other
100%	2297	1469
25%	0	2176
10%	0	1986
5%	0	164

Now consider the use of an injury criterion by which all the injured persons are constrained to be in the 100% sampling stratum. For example, say a person is "injured" if he was killed or if he was transported from the scene (according to the police report) and then hospitalized. The data are shown in Table 5-10. The problem of imprecise results and distorted crosstabulations due to a small number of injuries with high sampling weights has been eliminated because all injuries now have a sample weight of unity. Two other advantages of using "killed or transported-to-be-hospitalized" as an injury criterion are that:

- It has a much lower rate of missing data (0.03%) than AIS (20%)
- It is a tangible measure of injury severity, whereas AIS is a somewhat more abstract measure.

Therefore, it will be used as the primary injury criterion in the NCSS data.

5.2.2 How effectiveness is measured

The terms used in defining the effectiveness and benefits of Standards 203 and 204, as measured in the NCSS data, will now be explained and motivated one-by-one.

1. Post-Standard cars are those passenger cars that were manufactured after the Standard's effective date (January 1, 1968) plus those manufactured before the effective date which were equipped with a steering column EAD – i.e., 1967 GM and AMC cars and all 1968 and later cars. The 1967 Fords, which had a hub pad only, will be considered pre-Standard cars. Only passenger cars are studied – i.e., the light trucks on NCSS are excluded from the analysis.

2. Only those cars that were towed away due to damage are studied because NCSS is principally a towaway file.

3. Only frontal crashes are included, but with a broad definition of frontal: any vehicle with frontal damage (1st letter of CDC is F) or principal direction of force (11:00, 12:00 or 1:00). The purpose of this definition is to include any crash in which a person is likely to have primary contact with the steering assembly – i.e., any crash in which the Standards might be of potential benefit.

4. Only drivers are included. Other occupants may occasionally contact the steering assembly but not in the manner for which the Standards are designed to provide protection.

5. The injury criterion will be fatal or hospitalizing steering assembly contact injury. This means that the driver met criterion a, below, plus either criterion b1 or b2:

   a. The driver was killed or was transported-to-be-hospitalized (as defined in Section 5.2.1).

   b1. the driver's most severe injury involved steering assembly contact.

   b2. the driver's second most severe injury involved steering assembly contact and was rated AIS $\geq$ 3 or it had the same AIS as the most severe injury. (I.e., this injury by itself would probably have been sufficient to kill or hospitalize the driver.)

   There were 619 drivers on NCSS meeting criteria a and b1 and 149 that met a and b2. This is a total of 778 injured drivers.

From now on "fatal or hospitalizing steering assembly contact injury" will be abbreviated to "steering assembly contact injury."

Only the 2 most severe injuries were used in defining the injury criterion. It was felt that the 3rd most severe injury is generally not serious enough that it would, by itself, have necessitated hospitalization.

After the detailed analyses had been performed using the injury criterion defined above, it was found that the NCSS file contained 17 hospitalized drivers with multiple injuries whose 3rd most severe injury was caused by the steering assembly and was rated AIS 3-6. Since it is plausible that this injury, by itself, could have resulted in hospitalization, these 17 drivers could have been added to the 778 that met the above injury criterion. This would have increased the number of injuries by 2 percent. Since 2 of the 17 drivers were in pre-Standard cars and 15 in post-Standard cars (the same pre/post ratio as in the 778), their inclusion among the injured would not have changed the effectiveness estimate for Standards 203 and 204.

The NCSS file contained an additional 42 hospitalized drivers whose 3rd most severe injury was caused by the steering assembly and, although it was rated only AIS 1 or 2, it had the same AIS as the most severe injury. It could be argued, somewhat tenuously, that the 3rd injury by itself could have resulted in hospitalization and that these 42 drivers could also be added to the 778 and the 17 drivers mentioned above. This would have increased the number of injuries by another 5 percent. Since 39 of the 42 drivers were in post-Standard cars, the inclusion of the 42 would have lowered the effectiveness estimate for Standards 203 and 204 by 2 percent. This bias is much smaller than the 10 percent sampling error of effectiveness (see Section 5.2.3).

Since the impact of considering the 3rd injury in the injury criterion is small (especially so if the 42 cases with AIS 1 or 2 are excluded from consideration), it was decided not to redo the detailed analyses of Chapters 3, 5 and 6 with a revised injury criterion.

The motivation for using steering assembly contact injury as the measure of injury is that several other frontal crashworthiness standards more or less coincided with Standards 203 and 204 (see Chapter 3): specifically Standard 201 concerning the instrument panel and Standard 205 which improved the windshield. Thus, differences in overall injury rates between pre- and post-Standard 203 cars could be due, to a large extent, to these other Standards. On the other hand, differences in steering assembly injury rates would not likely be due to instrument panel or windshield improvements.

6. The injury rate is the number of drivers with steering assembly contact injury divided by the total number of drivers involved in frontal towaways. It is not the number of drivers with steering contact injury divided by the number of drivers with steering contact (injured plus uninjured): this definition cannot be used with NCSS because the investigators generally record contact points only if they caused medically documented injuries. Thus, if the Standards were effective in reducing injuries requiring transport or treatment to no injury or untreated minor injury, the denominator as well as the numerator of this latter injury rate would be smaller for post-Standard cars on NCSS. The effectiveness of the Standards would be underestimated.

The approach used in this evaluation - i.e., using the total number of involved drivers as the denominator - is based on the assumption that the proportion of drivers who actually contact the steering wheel (with or without injury - not necessarily recorded on NCSS) is the same for pre- and post-Standard cars after controlling for population differences (see 5.3.4), including the team-to-team differences of unknown contact point rates.

7. The likelihood of injury for drivers of post-Standards cars, R^+, is the hypothetical injury rate that would have occurred in 1978 if all cars on the road had met the requirements of Standards 203 and 204. R^+ is calculated from the simple injury rate (see preceding definition) by controlling for differences in the pre- and post-Standard accident population (see 5.2.4).

Similarly, the likelihood of injury for drivers of pre-Standard cars, R^-, is the hypothetical injury rate that would have occurred in 1978 if none of the cars on the road had met Standards 203 and 204.

8. The effectiveness, $\mathcal{E}$, of the combined Standards 203 and 204 is the relative difference of R^+, the post-Standard injury likelihood, and R^-, the pre-Standard injury likelihood:

$$\mathcal{E} = 100\,(1 - R^+ / R^-)\ \%$$

This is the proportion of steering assembly contact injuries eliminated as a consequence of equipment installed by manufacturers in response to the 2 Standards.

This chapter deals with the overall effectiveness of all the equipment actually installed in response to the 2 Standards combined. It does not attempt to give a detailed breakdown of effectiveness by Standard 203 versus Standard 204, or by improvements that were minimally required for compliance with the Standards versus simultaneous steering assembly improvements made in response to the Standards but not strictly required for compliance. These issues are addressed in Chapters 3 and 6.

9. The benefits are the total number of steering assembly contact injuries that the Standards would have prevented in 1978 if all passenger cars on the road had met the Standards' requirements. If N is the number of drivers involved in frontal towaways in 1978, u is the fraction of fatal or hospitalizing injuries on NCSS with unknown contact points, and t is the fraction of fatal or hospitalizing injuries which occur in towaways, then:

$$\text{Benefits} = \frac{(R^- - R^+)}{(1 - u)\, t} N = \varepsilon \frac{R^-}{(1 - u)\, t} N$$

This formula is based on the assumptions that the sampling errors in calculating R^- and R^+ from NCSS data are large relative to differences in ε between towaways with known contact points, towaways with unknown contact points and nontowaways.

Summary: The effectiveness of Standards 203 and 204 is defined here to be that part of the reduction in fatal or hospitalizing steering assembly contact injury rates of drivers involved in frontal towaway crashes which is attributable to equipment installed in response to the Standards.

5.2.3 The effectiveness of Standards 203 and 204

Standards 203 and 204 had an overall effectiveness of 38 percent in reducing fatal or hospitalizing steering assembly contact injury, according to the NCSS data. The observed effectiveness is significantly larger than zero and its confidence bounds extend from 28 to 48 percent. Table 5-11 summarizes the effectiveness findings. If all passenger cars on the road had been in compliance with Standards 203 and 204, the Standards would have prevented an estimated 24,200 fatal or hospitalizing steering assembly contact injuries in 1978. The confidence bounds on the benefits extend from 14,900 to 33,500 injuries prevented.

The injury reductions shown in Table 5-11 follow the definitions of effectiveness and benefits established in the previous section (5.2.2). The reductions are attributable to equipment installed in response to Standards 203 and 204: a modeling procedure has been applied to remove, insofar as possible, differences in the injury rates of pre- and post-Standard cars that are not due to the Standards. The modeling procedure is documented in the next section (5.2.4). The procedure for obtaining confidence intervals is described in Section 5.2.5.

TABLE 5-11

ESTIMATED EFFECTIVENESS AND BENEFITS OF STANDARDS 203 AND 204 FOR PASSENGER CAR DRIVERS IN FRONTAL IMPACTS, NCSS

Measure	Estimated Effectiveness/ Benefits	Confidence Bound Lower	Upper	Significantly Greater Than Zero?
Fatal or hospitalizing steering assembly contact injury reduction	38%	28%	48%	Yes
Fatal or hospitalizing steering assembly contact injuries prevented in 1978 (if all cars had complied)	24,200	14,900	33,500	Yes

5.2.4 Adjusting the NCSS data to remove confounding factors.

Table 5-12 is a simple NCSS tabulation of injury by Standard compliance. (Unless otherwise noted, the data in NCSS tabulations are weighted by the inverse sampling fractions.):

TABLE 5-12

STANDARD 203 AND 204 COMPLIANCE BY FATAL OR HOSPITALIZING STEERING CONTACT INJURY, DRIVERS IN FRONTAL TOWAWAYS, NCSS

Type of Car	Number of Drivers			Injury
	Injured	Not Injured	Total	Rate
Pre-Standard	124	3827	3951	3.14%
Post-Standard	654	31,659	31,659	2.07%

The injury rate of the drivers of post-Standard cars is 34.2 percent lower than the pre-Standard injury rate. This difference is partly due to the equipment installed in response to Standards 203 and 204, partly due to other differences between pre-Standard and post-Standard cars - confounding effects, and partly the result of team-to-team differences of missing contact point data rates (see Section 5.2.1). This section describes how the NCSS data were adjusted to remove the confounding effects, including the team-to-team differences which have already been discussed. After the adjustments, the difference of the injury rates increased from 34.2 percent (the simple difference observed in Table 5-12) to 38 percent - the effectiveness for Standards 203 and 204 based on NCSS data which was reported in the preceding section.

What are some of the potential confounding factors other than the team-to-team differences of missing data rates? The most obvious difference between the pre-Standard and post-Standard cars is that the former are older. The latter meet more of the Federal Motor Vehicle Safety Standards.

The other Federal standards that improved crashworthiness in frontal impacts are, primarily, Standard 201 governing the instrument panel, 205 and 212 relating to the windshield, 207 for seat performance, 208-210 on seat belts and anchorages and 214 for side structure integrity. These standards are discussed in more detail in Section 3.6.

The measure of effectiveness used here, however, is steering assembly contact injury reduction. An important reason for the choice of this measure is that Standards 201, 205, 212 and 214, which relate to other specific interior contact surfaces, are not likely to affect steering contact injury.

Standards 208-210 were accompanied by a significant increase in belt usage, which, in turn, led to decreased severity of steering column contact (see Sections 3.5 and 3.6). There are, however, many belt nonusers in the newest cars and some belt users even in cars of the early Sixties. Therefore, the confounding effect of belt usage can be removed by the adjustment technique described in this section.

This leaves Standard 207 - seat back strength - which may have led to a small casualty reduction in many types of frontal impacts, including steering assembly contacts (see Section 3.6). There are indications that the effect of Standard 207 on steering assembly contact injury is very small compared to that of Standards 203 and 204 [6]. The confounding effect of Standard 207 on the quantity sought in this evaluation is likely to be so small (under 1 percent) that it may be safely neglected here.

Since the pre-Standard cars are older than the post-Standard cars, they may be involved in different kinds of crashes and their drivers may have somewhat different characteristics. This is what is called the "age effect": occupants of older cars have higher injury rates, to some extent, because they are involved in more severe crashes. The modeling process used in this evaluation is especially suited for adjusting the pre- and post-Standard populations to remove the confounding effects of measurable differences in the distributions of observed variables such as Delta V, vehicle weight, occupant age and sex, crash mode, PDOF, etc.

There is also, possibly, an additional "age effect" due to underreporting of noninjury crashes involving older cars. If many noninjury crashes of old cars were unreported, there would be a higher injury rate among those crashes which are reported. This phenomenon is prevalent on State data files, where minor property damage crashes of old cars are not reported because they fail to meet the legal reporting criterion for value of the damage. The towaways on NCSS, on the other hand, are a more severe category of crashes: only 25-35 percent of police-reported crash-involved vehicles are towaways [63]. Relatively few towaways escape the legal reporting criteria, so not much of an age effect due to underreporting would be expected on NCSS.

The modeling process used in this evaluation is not suited for removing the confounding effect due to underreporting or other age effects that cannot be attributed to measurable differences in the distribution of the pre- and post-Standard populations for specific NCSS variables.

Therefore, two independent NCSS analyses were conducted to test for the presence of an "age effect" in the NCSS data. Both clearly demonstrated that there is no significant age effect other than the effects that can be controlled by the modeling process.

The first analysis was a weighted multiple regression of the steering contact injury rate by model year and Standard 203/204 compliance. In other words, the NCSS cases were tabulated by model year and the injury rate was calculated for each model year. The data points in the regression consisted of the model year and a 0 or 1 for Standard 203/204 noncompliance or compliance, respectively (independent variables); the injury rate for that model year (dependent variable) and the number of NCSS cases for that model year (regression weight). Table 5-13 lists the data points.

The multiple r^2 for the regression was .404, which was significantly greater than zero. (A fairly low r^2 is to be expected because the dependent variable - injury rate - is subject to sizable sampling error). The estimated regression coefficients are shown in Table 5-14.

The regression model clearly attributes almost the entire drop in steering contact injury rates to the intervention of Standards 203 and 204. Except for this intervention, the model year trend is virtually flat.

The data points and the regression lines are plotted in Figure 5-1. The pre-Standard data points (bold dots) have more year-to-year variability because the injury rates for these model years are based on smaller samples. Nevertheless, there are no more than 2 consecutive points above or below the flat pre-Standard regression line. The post-Standard data points (circles) obviously fit the flat post-Standard trend line well.

The second analysis was a comparison of fatal or hospitalizing injuries due to <u>known</u> contact sources <u>other than</u> the steering assembly. Injury rates were calculated in the pre-Standard 203/204 cars and the post-Standard cars for drivers in frontal impacts - i.e., analogous to the basic injury rates of this report (Table 5-12) except that instead of steering assembly contact, the injury was caused by any other known source. The results are shown in Table 5-15. The observed non-steering contact injury rate (3.08%) in the post-Standard

TABLE 5-13

DATA POINTS FOR REGRESSION OF STEERING CONTACT INJURY RATE
BY MODEL YEAR AND STANDARD 203/204 COMPLIANCE
(NCSS)

Model Year	Std. 203/204 Compliance	Injury Rate (%)	N of Drivers	Comments
"60"	0	1.44	348	60 was mean MY of pre-62 cars
62	0	3.23	217	
63	0	2.99	268	
64	0	2.31	694	
65	0	3.91	742	
66	0	4.22	1184	
67	0	1.81	498	'67 Fords & imports
67	1	1.78	1070	'67 GM, Chrysler & AMC
68	1	2.06	2180	
69	1	2.04	2546	
70	1	2.59	2698	
71	1	1.92	3132	
72	1	1.86	3493	
73	1	2.23	3365	
74	1	2.20	3182	
75	1	2.19	2332	
76	1	1.74	3158	
77	1	2.19	3065	
78	1	1.74	1438	

TABLE 5-14

ESTIMATED COEFFICIENTS FOR REGRESSION OF STEERING CONTACT INJURY RATE BY MODEL YEAR AND STANDARD 203/204 COMPLIANCE

Parameter	Estimated Regression Coefficient	t for Ho: parameter = 0	p>|t|
Intercept	3.13	1.39	.18
Std. 203/204 compliance	-1.07	-2.50	.02
Model year	0.0002	0.01	.99

TABLE 5-15

FATAL OR HOSPITALIZING INJURY RATES DUE TO KNOWN CONTACT POINTS OTHER THAN STEERING ASSEMBLY, DRIVERS IN FRONTAL TOWAWAYS, NCSS

Type of Car	N of Drivers	Non-Steering Injury Rate
Pre-Standard 203/204	3951	2.91%
Post-Standard 203/204	31,659	3.08%

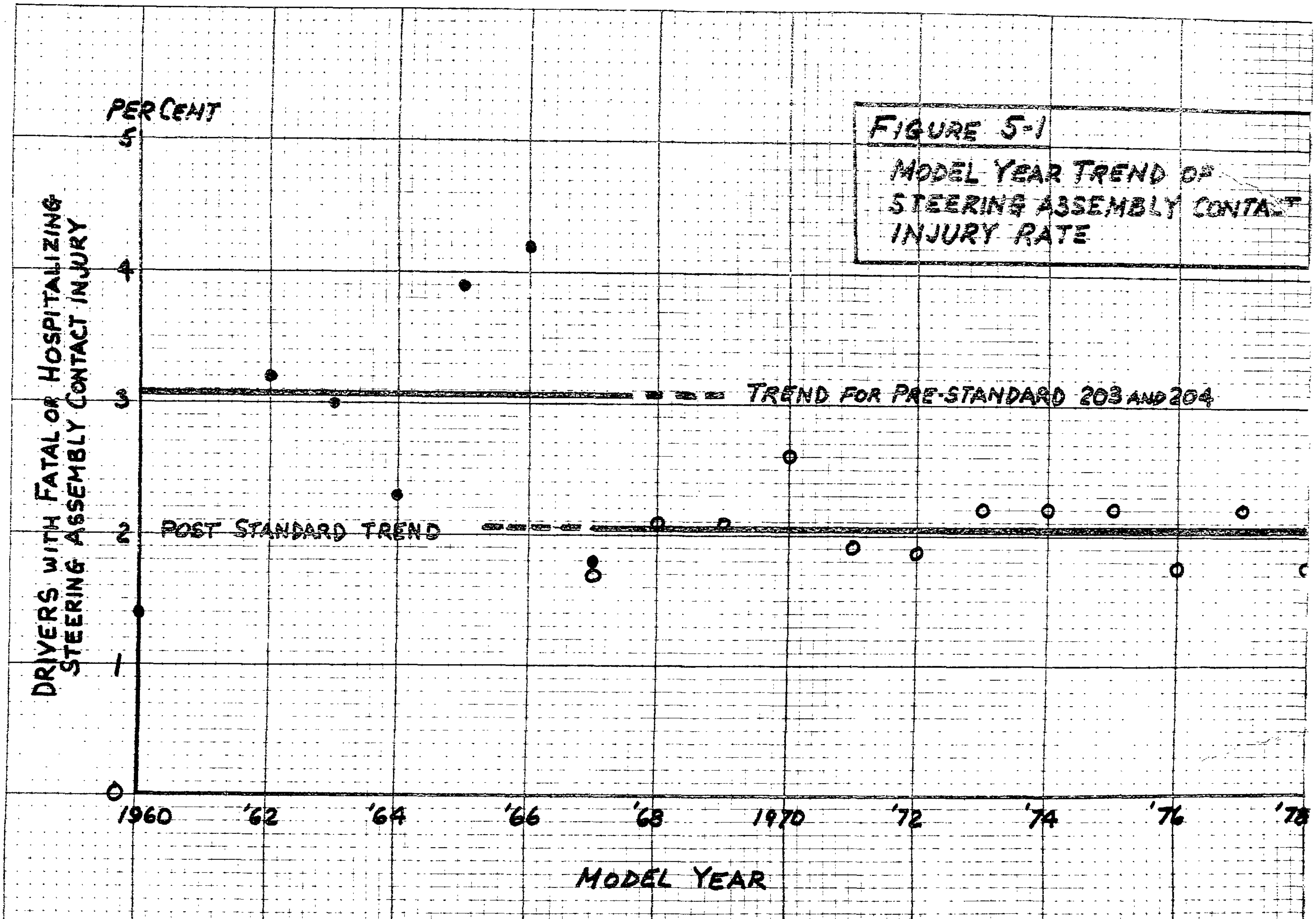


FIGURE 5-1
MODEL YEAR TREND OF
STEERING ASSEMBLY CONTACT
INJURY RATE
TREND FOR PRE-STANDARD 203 AND 204
POST STANDARD TREND
PER CENT
5
4
3
2
1
0
1960
'62
'64
'66
'68
1970
'72
'74
'76
'78
MODEL YEAR
DRIVERS WITH FATAL OR HOSPITALIZING
STEERING ASSEMBLY CONTACT INJURY

203/204 cars is 6 percent higher than the rate in the pre-Standard cars (2.91%). By contrast the steering assembly injury rate in the post-Standard cars (2.07% - see Table 5-12) is 34 percent lower than the rate in the pre-Standard cars (3.14%). The difference in the steering assembly and non-steering injury reductions,

$$1 - \frac{1 - .34}{1 + .06} = 38\%$$

is identical to the effectiveness claimed for Standards 203 and 204 on the basis of the modeling process described in the remainder of this section.

Why was the observed injury rate for known contacts other than the steering assembly higher for post-Standard than pre-Standard cars? It is the result of the bias discussed in Section 5.2.1 - viz., team-to-team differences in the rates of missing data on contact points. Table 5-16 shows the steering and non-steering injury rates after they have been adjusted for the control variable "team" (a procedure described in detail below). The adjusted post-Standard injury rate for non-steering contacts is 6.9 percent lower than the pre-Standard injury rate. By contrast, the adjusted post-Standard steering assembly contact injury rate is 41.5 percent lower than the pre-Standard rate. The difference in the adjusted steering assembly and non-steering injury reductions

$$1 - \frac{1 - .415}{1 - .069} = 37\%$$

is nearly the same as the effectiveness claimed for Standards 203 and 204 on the basis of the modeling process described below (38%).

Clearly, based on this analysis, Standards 203 and 204 are not "causing" any substantial reduction in non-steering contact NCSS injury. Conversely, based on the regression analysis, developments prior to and subsequent to Standards 203 and 204 were not

TABLE 5-16

FATAL OR HOSPITALIZING INJURY RATES, BY CONTACT SOURCES AND STANDARD 203/204 COMPLIANCE, ADJUSTED FOR TEAM-TO-TEAM DIFFERENCES, DRIVERS IN FRONTAL TOWAWAYS, NCSS

	Adjusted Injury Rates Due To:	
Type of Car	Steering Assembly Contact	Other Known Contact
Pre-Standard 203/204	3.49%	3.26%
Post-Standard 203/204	2.04%	3.04%
Reduction for post-Standard	41.5 %	6.9 %

"causing" any substantial reduction in non-steering contact NCSS injury. Conversely, based on the regression analysis, developments prior to and subsequent to Standards 203 and 204 were not "causing" any reduction in steering contact NCSS injury. The 2 analyses together, therefore, provide a strong degree of confidence that the steering contact injury reduction in NCSS, after adjustment for observable differences in the pre- and post- Standard accident populations, is indeed due to the equipment installed in response to Standards 203 and 204.

The modeling process that was used to adjust the NCSS data for observable population differences is in a sense analogous to stepwise regression. This process was developed because the potentially confounding factors on NCSS were far too numerous for a simultaneous analysis such as GENCAT or CONTAB in its ordinary form. The starting point is the simple injury rate comparison - Table 5.12 - where the post-Standard cars have a 34.2 percent lower injury rate than the pre-Standard cars. A list of potential control variables - confounding factors - is drawn from the NCSS data elements. For each potential control, the 3 way table of Standard 203/204 compliance by injury by the control variable is formed. The cell entries are smoothed by multi-dimensional contingency table analysis. The marginals of the pre and post Standard populations are adjusted to have the same distribution of the control variable and the injury reduction for post-Standard cars versus pre-Standard is recalculated using the "expected" cell entries. The control variable which results in the greatest deviation of adjusted injury reduction from the starting point (34.2 percent) is chosen as the first control variable. This is the "first step" of the "stepwise regression." Next, for each of the remaining control variables, the 4 way table of Standard 203/204 compliance by injury by the first selected control by that variable is formed. The cell entries are smoothed by multidimensional contingency table analyses. The marginals of the pre- and post-Standard populations are adjusted (using the smoothed cell entries) to have similar marginal distributions in the control variables and the injury reduction for post-Standard cars is recalculated. The control variable which results in the greatest deviation from the previous step is chosen as the second control variable. This is the "second step." The process continues until none of the unselected remaining controls has an effect as large as 1 percent or until the tables become too large for the amount of data available. The injury reduction calculated in the last step, 38.4 percent, is the estimate of the Standards' effectiveness based on NCSS.

What does it mean to "adjust the marginals of the pre- and post-Standard populations to have the same distribution of the control variable and recalculate injury reduction"? The process is illustrated by the fictitious example for a hypothetical FMVSS 800 in Table 5-17. Note that the injury reduction in the unadjusted data (53 percent) greatly overstates the effectiveness of the Standard. The reduction is, to a large extent, due to the fact that post-Standard vehicles had less severe accidents (only 20 percent had Delta V $\geq$ 20, as opposed to 60 percent for the pre-Standard cars.) After adjusting the marginals so that the pre- and post-Standard vehicles have the same marginal Delta V totals - viz., the marginal Delta V totals of the combined pre- and post-Standard populations in the raw data - the injury reduction drops to 35 percent.

The modeling procedure will now be documented step by step:

TABLE 5-17

FICTITIOUS EXAMPLE SHOWING TECHNIQUE OF
ADJUSTING THE MARGINALS TO EVALUATE "FMVSS 800"

(a) Unadjusted (raw) data

	Pre-FMVSS 800 cars			FMVSS 800 cars		
	$\Delta V < 20$	$\Delta V \geq 20$		$\Delta V < 20$	$\Delta V \geq 20$	
AIS ≥ 2	100	300	400	240	140	380
	25%	50%	40%	15%	35%	19%
AIS < 2	300	300	600	1360	260	1620
	75%	50%	60%	85%	65%	81%
	400	600		1600	400	

$$\text{Injury reduction before adjustment} = \frac{.4 - .19}{.4} = 53\ \%$$

(b) Adjusted data

	Pre-FMVSS 800			Post-FMVSS 800		
	$\Delta V < 20$	$\Delta V \geq 20$		$\Delta V < 20$	$\Delta V \geq 20$	
AIS ≥ 2	500	500	1000	300	350	650
	25%	50%	33%	15%	35%	22%
AIS < 2	1500	500	2000	1700	650	2350
	75%	50%	67%	85%	65%	78%
	2000	1000		2000	1000	

$$\text{Injury reduction after adjustment} = \frac{.333 - .216}{.333} = 35\%$$

Step 1: Calculate unadjusted injury reduction - The basic NCSS tabulation of fatal or hospitalizing steering assembly contact injury by Standard 203/204 compliance was presented in Table 5-12 and it was the following:

	Injured	Uninjured	
Pre	124	3827	3951
Post	654	31,005	31,659
	778	34,832	35,610

The injury reduction for post-Standard cars is:

$$1 - (654/31{,}659) \,/\, (124/3951) = 34.2\%$$

Another way to carry out the arithmetic is:

$$1 - \frac{\frac{654}{31{,}659}\ 35{,}610}{\frac{124}{3951}\ 35{,}610} \quad = \quad 1 - \frac{735.62}{1117.60} \ = 34.2\% \qquad (1)$$

Equation (1) says that if all cars on NCSS had complied with Standard 203/204 and if there are no confounding effects, then there would have been 735.62 injured drivers. If none of the cars had complied with Standards 203/204 there would have been 1117.60 injuries. Equation (1) is useful because it has the same structure as the formulas that will be used in subsequent steps to calculate adjusted injury reduction.

Step 2 - Select potential control variables - After inspection of the NCSS file, literature review and discussion with NHTSA engineers, a selection of control variables was made. A NCSS variable was selected if it was suspected of having a strong relationship with injury risk and a different distribution for pre- and post-Standard cars or if the effectiveness of the

Standards was thought to vary considerably for different values of the control variable. This is precisely what a "confounding effect" is. Moreover, the NCSS team was included among the potential control variables because it has a strong relationship with the missing data rate on contact points (which in turn affects the observed injury risk) and a different distribution for pre- and post-Standard cars (see Table 5-8). In all, 10 variables were selected:

(1) Occupant's age

(2) Occupant's sex

(3) Belt usage

(4) Vehicle weight

(5) Delta V

(6) Type of vehicle/object struck

(7) Principal direciton of force (PDOF)

(8) Damage location - horizontal

(9) Damage location - vertical

(10) NCSS team.

Step 3 - Categorize control variables - Since the modeling process will employ multidimensional contingency table analysis [42], it is necessary that each control variable be categorical in nature and, preferably, that it have few categories. Continuous variables such as Delta V are subdivided into class intervals. Variables that are categorical in nature but have many categories (Damage location - horizontal) are collapsed to a smaller number of alternatives. The categorization used for the 10 potential controls, as well as the proportion of NCSS cases in each category, is shown in Table 5-18. Delta V of 15 was chosen as a break point because it is the test velocity for Standard 203.

At this point, a BMDP [14] file containing the 10 control variables, injury, pre-post and the NCSS case weight is created. (See Appendix A for the creation statements.)

TABLE 5-18

CATEGORIZATION OF CONTROL VARIABLES
PERCENT OF NCSS CASES IN EACH CATEGORY

Vehicle	1st Category (%)	2nd Category (%)	3rd Category (%)
1. Age	LT 39 (74)	GE 40, Unk. (26)	
2. Sex	M (69)	F, Unk. (31)	
3. Belt Usage	No, Unk. (89)	Yes (any type) (11)	
4. Veh. Weight	LT 3500, Unk. (50)	GE 3500 (50)	
5. Delta V	1 - 14 (43)	GE 15 (16)	Unk. (41)
6. Vehicle/ Object Struck	Vehicle lighter than 10,000 lbs. (63)	Fixed Object or Veh. GE 10,000 (37)	
7. PDOF	12, 0 (52)	11,10, 1, 2 (48)	
8. Damage - vertical (3rd letter of CDC)	E (90)	All other (10)	
9. Damage - horiz. (1st 2 letters of CDC)	FD, FC (28).	FY, FZ, FL FR, L., R. (72)	
10. NCSS team	1st	2nd	3rd
	Calspan (15)	HSRI (9)	Indiana (12)
	4th	5th	6th
	Kentucky (12)	Miami (16)	SWRI (28)
	7th		
	DySci (8)		

Step 4 - Test interaction of control variables with the Standards

It is impossible to apply a multidimensional contingency table analysis program directly to the full 12-way crosstabulation of injury, pre-post and the 10 control variables: the existing programs typically allow 6 dimensions. If some of the control variables could be discarded, it would simplify the modeling process.

If a potential control variable has the same distribution within the pre- and post-Standard accident populations, there will be no change in the injury reduction attributed to the Standard after the marginals are adjusted for this control variable (for proof see [68], pp. 30-31). For this reason, Reinfurt and Hochberg recommend that each potential control variable be tested for interaction with pre-post and that those with no significant interaction be discarded [67].

Table 5-19 shows, for each control, the results of the ordinary Chi-square tests applied to the 2-way table of pre-post by the control variable. (The 2-way tables themselves may be obtained from Appendix B.)

All of the potential controls interact significantly ($\alpha = .01$) with the Standards except Delta V - i.e., the pre-Standard and post-Standard cars have about the same Delta V distribution. Thus, Delta V alone among the 10 variables could be considered for discarding based on this test. Since Delta V is widely considered a major determinant of injury risk (see, for example, [32]), it was decided not to discard any of the controls at this point.

Step 5 - Test interaction of controls with injury risk and Standard effectiveness

If the injury rates are the same, across all values of the control variable, within the pre-Standard population and also within the post-Standard population then there will be no

TABLE 5-19

CHI-SQUARE VALUES FOR 2 WAY TABLE OF STANDARD 203/204 COMPLIANCE BY CONTROL VARIABLE

	Control Variable	Chi-square	df
1.	Age	79.5	1
2.	Sex	109.8	1
3.	Belt usage	139.2	1
4.	Vehicle veight	18.0	1
5.	Delta V	1.8	2
6.	Vehicle/object struck	8.6	1
7.	PDOF	20.2	1
8.	Damage - vertical	28.5	1
9.	Damage - horizontal	5.9	1
10.	NCSS team	1048.2	6

change in the injury reduction attributed to the Standard after the marginals are adjusted (see [68], p. 30). The above stipulations amount to saying that

- The control variable does not affect injury risk
- The Standards are equally effective for all values of the control variable.

For this reason, Reinfurt and Hochberg [67] recommend testing each control for simple interaction with injury and 3-way interaction with injury and pre-post. If neither interaction is significant, the control is discarded.

Table 5-20 shows, for each control, the Chi-square values for the injury x control and the injury x pre-post x control terms generated by the BMDP analysis [14] of the 3-way table of pre-post by injury by the control variable. (The BMDP runs themselves are presented in Appendix B.)

TABLE 5-20

CHI-SQUARE VALUES OF INJURY x CONTROL AND INJURY x PRE-POST x CONTROL FOR 3 WAY TABLE OF INJURY BY PRE-POST BY CONTROL, BMDP

Control	Injury x Control		Injury x Pre-Post x Control	
Variable	Chi-Square	df	Chi-Square	df
1. Age	32.3	1	1.4	1
2. Sex	1.8	1	2.1	1
3. Belt usage	29.1	1	4.2	1
4. Vehicle weight	0.2	1	0.0	1
5. Delta V	665.9	2	1.2	2
6. Vehicle/object struck	154.4	1	0.4	1
7. PDOF	88.9	1	2.7	1
8. Damage - vertical	4.3	1	0.0	1
9. Damage - horiz.	60.3	1	0.6	1
10. NCSS Team	83.1	6	8.1	6

Driver sex, vehicle weight and damage-vertical interact significantly with neither injury nor injury x prepost ($\alpha = .01$). Alpha = .01 is used rather than .05 because the Chi-squares are calculated for weighted NCSS data and are overstated. Since driver sex had exceptionally high interaction with the Standards (Table 5-19), it was decided to retain it. Vehicle weight and damage-vertical were discarded. Table 5-20 also shows that Delta V interacts more strongly with injury than any other variable. This confirms the decision made in Step 4 to retain it in the modeling process.

Step 6 - Obtain 3-way tables of pre-post x injury x control for each of the remaining control variables. Up to this point, the original 12-way table has been reduced to a 10-way table - far too large for direct analysis. Even if sex and Delta V had been discarded as controls, the resultant 8-way table could not have been analyzed. At this point, the "stepwise" introduction of control variables begins. The first task is the formation of the 3-way tables - the tables themselves may be found in Appendix B.

Step 7 - Fit the best model to each 3-way table - There are only 124 injured drivers of pre-Standard cars on NCSS. When these cases are tabulated across several control variables, there will be cells with rather small counts. These cells have high relative sampling error. When the marginals are adjusted - i.e., weighted by the (primarily post-Standard) overall population - these small cell counts may be weighted heavily and contribute large absolute sampling error. For example, the small number of belted drivers of pre-Standard cars will be heavily weighted due to the much higher proportion of belt users in the post-Standard cars.

The risk of large error due to heavy weighting of small counts can be reduced by "smoothing" the cell counts using multidimensional contingency table analysis and calculating adjusted effectiveness using the "expected" cell entries. Reinfurt and Hochberg [67] applied this technique in their calculation of safety belt effectiveness.

The BMDP contingency table analysis program [14] is used to analyze each of the 3-way tables generated above. The program generates a Chi-square statistic for each of the 2- and 3- way interactions. (Specifically, the program calculates the likelihood ratio Chi-square for removing an n-way interaction from the model consisting of all n-way and lower interactions.) With this information, it is possible to fit a model - a set of "important" interactions between the variables - that gives a good prediction of the observed table entries. In general, it was attempted to find the model with the most degrees of freedom for which the observed entries did not differ significantly ($\alpha = .01$) from the predicted.* In some cases, the choice of a model was self-evident; in others, several models were fit to the data and one selected. Appendix B shows each of the models tested and their Chi-square values. Table 5-21 lists the models that were selected.

TABLE 5-21

MODELS SELECTED FOR FITTING 3 WAY TABLES

S = Standard 203/204 compliance
I = Injury

C = Control Variable =	Best-Fitting Model**	df	Chi-square	P
Age	SI, SC, IC	1	1.4	.23
Sex	SI, SC, IC	1	2.1	.14
Belt use	SI, SC, IC	1	4.2	.04
Delta V	SI, SC, IC	2	1.2	.55
Vehicle/object struck	SI, SC, IC	1	0.4	.51
PDOF	SI, SC, IC	1	2.7	.10
Damage-horizontal	SI, SC, IC	1	0.6	.42
Team	SI, SC, IC	6	8.1	.23

**also includes lower-level interactions using subsets of the variables - e.g., "SI" includes S and I.

*A model with p slightly $<$ .01 was accepted if it meant a large gain in df.

Step 8 - Obtain 3-way tables of expected cell entries of pre-post x injury x control, for each of the 8 control variables, using the models listed in Table 5-21. The tables of expected values are in Appendix B.

Step 9 - Calculate adjusted injury reduction using each of the 3-way tables of expected cell entries obtained in Step 8. The confounding effect of each control variable is separately assessed by calculating, for each 3-way table, the injury reduction attributable to the Standards after the marginals are adjusted to have the same distribution of the control variable. For example, the 3-way table of expected cell entries using driver age as the control:

	Age < 40				Age ≥ 40		
	Injured	Uninjured			Injured	Uninjured	
Pre	72.185	2619.816	2692.001	Pre	51.814	1207.185	1258.999
Post	430.815	23267.180	23697.995	Post	223.186	7737.813	7960.999
			26238.996				9219.998

If none of the cars had complied with Standards 203 and 204, there would have been

$$(72.185/2692.001)26389.996 + (51.814/1258.999)9219.998 = 1087.09 \text{ injuries}$$

If all of the cars had met the Standards, there would have been

$$(430.815/23697.995)26389.996 + (223.186/7960.999)9219.998 = 738.24 \text{ injuries}$$

Thus, after controlling for driver age, the injury reduction attributed to the Standards is

$$(2) \qquad 1 - \frac{738.24}{1087.09} = 32.1\%$$

Now compare Equation (2) above with Equation (1) which was derived in Step 1 and dealt with unadjusted data:

$$(1) \qquad 1 - \frac{735.62}{1117.60} = 34.2\% \text{ unadjusted injury reduction.}$$

Because the pre-Standard cars are driven by older persons and because older drivers have intrinsically higher injury risk, the prediction, from the raw pre-Standard injury rate, of how many persons would be injured if no cars met the Standards, 1117.60, is biased upwards. Controlling for driver age removes this bias and yields a better prediction, 1087.09. Thus, also, it removes a bias in the opposite direction in the estimate of injuries if all cars met the Standards. As a result, the injury reduction attributed to the Standards is only 32.1% after removing the upward-confounding effect of driver age differences in the pre and post-Standard populations.

Table 5-22 shows the results of using each of the control variables, based on the same calculations as were used in the driver age example above. Note that all entries in the table are subject to sampling error, including the net effects of the control variables (the right-hand column). Thus, it is even possible that a control has a positive effect when a negative effect is expected. In the case of driver sex, however, the positive effect observed in NCSS is the expected one: more men drive old cars; men have lower injury risk; the raw injury rate for pre-Standard cars is thus biased downwards and rises after adjusting for this factor. Similarly, in the case of NCSS team, a positive effect is expected (see Section 5.2.1).

Step 10 - Select NCSS Team - the control variable whose adjustment causes the largest change in the injury reduction attributed to the Standards (+7.3, according to Table 5-22). It was shown in Section 5.2.1 that the team-to-team differences in contact point missing data

TABLE 5-22

INJURY REDUCTION ATTRIBUTED TO STANDARDS 203 AND 204
AFTER ADJUSTING FOR 1 CONTROL VARIABLE

Control Variable	Adjusted Injury Reduction (%)	Change From Unadjusted (%)
None	34.2	
Age	32.1	-2.1
Sex	34.7	+0.5
Belt use	32.0	-2.2
Delta V	33.7	-0.5
Vehicle/object struck	32.7	-1.5
PDOF	32.5	-1.7
Damage-horizontal	33.4	-0.8
Team	41.5	+7.3

would bias the measurement of steering assembly contact injury reduction. It is evident from Table 5-22 that this bias is large relative to the confounding effects of the other potential control variables.

Step 11 - Check if any unselected variables have 1 percent effect or more. Table 5-22 shows that adjustment for age (-2.1), belt use (-2.2), vehicle/object struck (-1.5) and PDOF (-1.7) each would have resulted in a greater than 1 percent change in the injury reduction attributed to the Standards. Although team has the largest confounding effect, it is reasonable to believe that further adjustment using an additional control variable may still result in a measurable change in the injury reduction.

Step 12 - Obtain 4-way tables of pre-post x injury x team x control, for each of the remaining control variables. The tables are in Appendix B.

Step 13 - Fit the best model to each 4-way table - Appendix B shows each of the models tested and their Chi-square values. Table 5-23 lists the models that were selected.

TABLE 5-23

MODELS SELECTED FOR FITTING 4-WAY TABLES

S = Standard 203/204 compliance
I = Injury
T = Team

C = 2nd Control Variable=	Best-Fitting Model	df	Chi-square	P
Age	STC, SI, IT, IC	19	25.6	.14
Sex	STC, SI, IT	20	38.9	.01
Belt use	STC, SI, IT, IC	19	28.0	.08
Delta V	STC, ITC, SI	20	22.1	.33
Vehicle/object struck	STC, ITC, SI	13	19.0	.12
PDOF	STC, SI, IT, IC	19	32.0	.03
Damage-horizontal	STC, SI, IT, IC	19	23.1	.23

Step 14 - Obtain 4-way tables of expected cell entries of pre-post x injury x team x control, for each of the remaining control variables, using the models listed in Table 5-23. The tables of expected values are in Appendix B.

Step 15 - Calculate adjusted injury reduction using each 4-way table of expected cell entries. The procedure is identical to Step 9, except for one detail: a constant of 0.05 was added to each "observed" cell prior to generating the "expected" 4-way tables. The added constant is necessary for successful operation of the BMDP program when there are many cells (i.e., 4-way tables or larger in the problem under consideration). Since there are fewer pre-Standard injuries than post-Standard injuries or noninjuries, the added constant on each cell makes a larger relative contribution to the total of pre-Standard injuries than to the other categories. As a result the adjusted pre-Standard injury rate, based on the "expected" table, is biased slightly upwards and so is the calculated effectiveness. These biases (which were about 0.3 percent in the 4-way tables and 0.5 percent in the 5-way tables) have been subtracted from the adjusted effectiveness values shown in Tables 5-24 and 5-26.

The adjusted injury reductions using each of the 4-way tables are shown in Table 5-24.

TABLE 5-24

INJURY REDUCTION ATTRIBUTED TO STANDARDS 203 AND 204
AFTER ADJUSTING FOR 2 CONTROL VARIABLES

Control Variables	Adjusted Injury Reduction (%)	Change in Reduction (%)	
		Cumulative	Incremental
None	34.2		
Team	41.5	+7.3	
Team, age	39.8	+5.6	-1.7
Team, sex	41.4	+7.2	-0.1
Team, belt use	39.7	+5.5	-1.8
Team, delta V	39.8	+5.6	-1.7
Team, vehicle/object struck	40.0	+5.8	-1.5
Team, PDOF	39.7	+5.5	-1.8
Team, damage-horizontal	40.7	+6.5	-0.8

Step 16 - Select PDOF, one of the control variables whose adjustment causes the largest incremental change in the injury reduction attributed to the Standards (-1.8, according to Table 5-24). Adjustment for belt usage results in the same change. But PDOF was selected in preference to belt usage because

- PDOF was considered an important factor in the clinical analysis of steering assembly contact injury (see Sections 3.3.3 and 3.5).
- PDOF is associated with 2 of the other variables - vehicle/object struck and damage-horizontal - and may subsume their confounding effects.

- There are relatively few pre-Standard belt users on the NCSS file. If they were further categorized by an additional control variable, a meaningful contingency table analysis could not be performed. So, if "belt use" were selected as the control variable at this point, the control and adjustment process would have to stop here.

Step 17 – Check if any unselected variables have 1 percent effect or more. Table 5-24 shows that adjustments for age (-1.7), belt use (-1.8), Delta V (-1.7) and vehicle/object struck (-1.5) each would have resulted in a greater than 1 percent incremental change in the injury reduction attributed to the Standards. It is reasonable to believe that further adjustment using an additional control variable may still result in a measurable change in the injury reduction.

Step 18 – Obtain 5-way tables of pre-post x injury x team x PDOF x control, for each of the remaining control variables. The tables are in Appendix B.

Step 19 – Fit the best model to each 5-way table – Appendix B shows each of the models tested and their Chi-square values. Table 5-25 lists the models that were selected.

Step 20 – Obtain 5-way tables of expected cell entries of pre-post x injury x team x PDOF x control, for each of the remaining control variables, using the models listed in Table 5-25. The tables of expected values are in Appendix B.

Step 21 – Calculate adjusted injury reduction using each 5-way table of expected cell entries, with correction for the bias introduced by adding 0.05 to each cell. The adjusted injury reductions are shown in Table 5-26.

TABLE 5-25

MODELS SELECTED FOR FITTING 5-WAY TABLES

S = Standard 203/204 compliance

I = Injury

T = Team

P = PDOF

C = 3rd Control Variable =	Best-Fitting Model	df	Chi-square	P
Age	STPC, ITP, SI, IC	40	49.1	.15
Sex	STPC, ITP, SI, IC	40	62.9	.01
Belt use	STPC, ITP, SI, IC	40	59.2	.02
Delta V	STPC, ITC, ITP, SI	55	65.4	.16
Vehicle/object struck	STPC, ITC, IPT, SI	34	47.9	.05
Damage-horizontal	STPC, ITP, SI, IC	40	57.0	.04

TABLE 5-26

INJURY REDUCTION ATTRIBUTED TO STANDARDS 203 AND 204
AFTER ADJUSTING FOR 3 CONTROL VARIABLES

		Change in Reduction (%)	
Control Variables	Adjusted Injury Reduction (%)	Cumulative	Incremental
None	34.2		
Team	41.5	+7.3	
Team, PDOF	39.7	+5.5	
✓Team, PDOF, age	38.4	+4.2	-1.3
Team, PDOF, sex	41.0	+6.8	+1.3
Team, PDOF, belt use	38.9	+4.7	-0.8
Team, PDOF, Delta V	39.2	+5.0	-0.5
Team, PDOF vehicle/object struck	39.4	+5.2	-0.3
Team, PDOF, damage-horizontal	39.9	+5.7	+0.2

Step 22 - Select driver age, one of the control variables whose adjustment causes the largest incremental change in the injury reduction attributed to the Standard (-1.3 according to Table 5-26). Adjustment for driver sex would have resulted in an equally large change in the opposite direction. But age was selected in preference to driver sex because

- 4 of the potential control variables, including age, result in lowering the effectiveness, but only 2, including sex, result in increased effectiveness - i.e., since the trend of the remaining control variables is generally downwards, choose the variable which results in a downward adjustment.

Step 23 - Check if further adjustment is feasible - The 124 injured drivers of pre-Standard cars have, up to this point, been spread among 28 cells (7 teams x 2 PDOF groups x 2 age groups).

Thus, there are an average of 4.4 observations per cell. It would not be advisable to spread the data any thinner for contingency table analysis, so the process must stop here.

Table 5-26 shows that only adjustment for driver sex, among the unselected controls, would have resulted in an incremental change greater than 1 percent and just barely so (+1.3). The upward adjustments due to sex and damage-horizontal sum up to 1.5 percent. The downward adjustments due to belt use, Delta V and vehicle/object struck sum up to 1.6 percent. So very little net observable bias, if any, remains in the data.

Step 24 - Stop: Select team, PDOF and age - the effectiveness of Standards 203 and 204 in the NCSS data is 38.4 percent. This is the injury reduction attributable to the Standards after adjusting for the 3 variables which had the largest confounding effects (Table 5-26).

The post-Standard cars:

- are more common in areas covered by NCSS teams with low missing data rates on contact points and as a result have spuriously high steering assembly contact injury rates (see Section 5.2.1).
- have more angle-frontal collisions, which are less likely to result in steering assembly contact injury (See Tables 3-10 and 6-26).
- have younger drivers, who have lower injury risk.

Therefore, the observed reduction of fatal or hospitalizing steering assembly contact injuries, which was 34.2 percent unadjusted, is 38.4 percent after adjustment for team, PDOF and driver age. This is the effectiveness claimed for the Standards in Table 5-11.

A check for the validity of the modeling and adjustment process was given at the beginning of this section: the unadjusted reduction of steering assembly contact injury (Table 5-12) relative to the reduction of non-steering contact injury (Table 5-15) was 38 percent.

When the adjusted injury reduction is computed for the 5-way table of expected cell entries in the selected model (controlling for team, PDOF and age), it is found that 1185.32 injuries would have occurred if none of the cars had complied with Standards 203 and 204 and 730.27 would have occurred if all cars had complied. (The procedure for this calculation was described in Step 9. A correction has been made for the bias due to adding 0.05 to each cell. Note that 1-(730.27/1185.32) = 38.4%.) Thus, in the nomenclature of Section 5.2.2,

R^- = NCSS steering assembly contact injury rate if no cars comply = 1185.32/35,610

R^+ = NCSS steering assembly contact injury rate if all cars comply = 730.27/35,610.

The <u>benefits</u> of Standards 203 and 204 - the total number of steering assembly contact injuries that the Standards would have prevented in 1978 if all passenger cars on the road had been in compliance - are estimated as follows: the formula for benefits that was developed in Section 5.2.2 was

$$\text{Benefits} = \frac{(R^- - R^+)}{(1 - u)\, t} \quad N$$

where

N = U.S. number of drivers in frontal towaways in 1978

u = fraction of frontal driver injuries on NCSS with unknown contact point

t = fraction of hospitalizing injuries occurring in towaways.

On November 16, 1979, the NCSS file contained 873 passenger car fatalities with known damage location and 35,610 drivers in frontal towaways. The 1978 FARS file contains 28,411 fatalities. Thus an estimate of N would be

$$N = \frac{28{,}411}{873}\ 35{,}610 = 1{,}159{,}000$$

A total of 2297 frontally involved NCSS drivers were killed or transported to be hospitalized; 679 of them had unknown interior contact points. Thus

$$u = \frac{679}{2297}$$

In Oakland County, Michigan, 1973, there were 1629 crash-involved drivers with K or A level injury ([63], p. 177). Of these, 1414 occurred in towaways, including all of the fatalities. Now, "K+A" and "fatal or hospitalizing" are fairly comparable levels of injury severity. For example, in the Restraint Systems Evaluation Project, there were 1008 cases of K+A and 1005 persons killed or hospitalized ([55], pp. 34-35). So it is likely that they are similarly distributed between towaways and nontowaways. Thus,

$$t = \frac{1414}{1629}$$

Finally,

$$\text{Benefits} = (1185.32 - 730.27)\ \frac{28{,}411}{873}\ \frac{2297}{1618}\ \frac{1629}{1414} = 24{,}200$$

fatal or hospitalizing injuries prevented in 1978, nationwide, if all passenger cars had complied with Standards 203 and 204. This is the estimate entered in the last row of Table 5-11.

The procedure for estimating benefits can also be used to estimate the magnitude of <u>the problem</u> of steering assembly contact injuries if Standards 203 and 204 had not been promulgated. The following procedure was used to obtain the estimates in Table 3-3:

R^- = NCSS steering assembly contact injury rate if no cars comply

= 1185.32/35,610

I_s = number of steering assembly contact injuries that would have occurred in 1978

$$= \frac{R^-}{(1-u)t} N$$ (where u, t and N are as in the preceding calculation of benefits)

$$= 1185.32 \; \frac{28{,}411}{873} \; \frac{2297}{1618} \; \frac{1629}{1414} = 63{,}100$$

Since 58 percent of the driver hospitalizations in frontal impacts of pre-Standard cars were due to the steering assembly alone or the steering assembly plus another contact (Table 3-2),

I_f = number of driver injuries (involving fatality or hospitalization) in frontal crashes in 1978, if no cars comply

$= I_s$ / .58 = 108,800

In the pre-Standard cars, 46.3 percent of the driver hospitalizations in frontal crashes were due primarily to steering assembly contact (Table 3-2). Thus, there would have been .463 I_f = 50,400 of these injuries in 1978 if Standards 203 and 204 had not been promulgated. Similarly, there would have been .117 I_f = 12,700 hospitalizations due to steering assembly contact plus another contact source. There would have been .42 I_f = 45,700 drivers killed or hospitalized in frontal crashes as a result of contacts other than the steering assembly.

The NCSS file also contains records of 1349 passenger car drivers who were killed or hospitalized in non-frontal towaway crashes and 2110 automobile passengers who were killed or hospitalized in frontal crashes. These casualties are not significantly affected by the presence or absence of Standards 203 and 204. Thus, national estimates of casualties in 1978, if no cars comply with Standards 203 and 204, are simply given by

$$1349 \; \frac{28,411}{873} \; \frac{1629}{1414} = 50,600 \text{ drivers in non-frontal crashes}$$

$$2110 \; \frac{28,411}{873} \; \frac{1629}{1414} = 79,100 \text{ passengers}$$

These numbers are added to I_f to obtain the estimates of fatalities and hospitalizing injuries in all types of crashes that are shown in Table 3-3.

5.2.5 Measurement of sampling error

A jackknife procedure was used to obtain confidence intervals for the NCSS estimates of effectiveness and to test hypotheses. The procedure is described step-by-step in this section - but, first, some comments on why it was selected.

The effectiveness estimate (Section 5.2.4) involved a relatively complex procedure: to begin with, NCSS is a stratified sample with unequal sampling proportions. The NCSS data were classified by pre-post, injury severity, NCSS team, PDOF and driver age. A model was fit to the 5-way table. The "expected" table was adjusted so that the pre and post cases would have identical marginal distributions of the 3 control variables. Finally, the ratio of ratios of injuries to exposed drivers was calculated.

There is no formula for calculating directly the variance of the estimated effectiveness. Even if there were, the variance estimated from the sample could be substantially in error because the data were divided among a large number of cells.

On the other hand, the jackknife procedure has been found excellent for obtaining generally reliable approximations to the variance for estimators like these [53].

What is the motivation for the jackknife procedure? Ideally, the variance could have been estimated as follows: number all the NCSS cases. Split the NCSS sample into 10 groups according to the last digit of the case number. Estimate effectiveness separately within each of the 10 subsamples. This gives 10 independent estimates of effectiveness, $\varepsilon_1, \ldots, \varepsilon_{10}$, each based on a tenth of NCSS. Let

$$\bar{\varepsilon} = \left(\sum_{1}^{10} \varepsilon_i\right) / 10$$

$$s^2 = \left(\sum_{1}^{10} (\bar{\varepsilon} - \varepsilon_i)^2\right) / 9$$

Then s^2 is an estimate of the variance of effectiveness based on a tenth of NCSS. The variance of the effectiveness using all of NCSS is $s^2 / 10$.

Unfortunately, this approach cannot be used. It required estimating effectiveness separately for each tenth of the NCSS file. A tenth of NCSS does not contain enough cases to apply the modeling process developed in the preceding section.

The jackknife procedure circumvents that problem. Instead of effectiveness being calculated for one tenth of NCSS, it is computed for the nine tenths of NCSS that remain after removing a tenth of the file. Nine tenths of NCSS does contain enough cases to apply the modeling process developed in the preceding section. Let $\varepsilon_{(1)}, \ldots, \varepsilon_{(10)}$ be the estimates of effectiveness, each based on 9/10 of NCSS, i.e., all of NCSS except the 1st, ..., 10th subsample, respectively. Let ε = 38.4% be the effectiveness estimate based on all NCSS (i.e., the main result of the preceding section). Let

$$\varepsilon_{*i} = 10\varepsilon - 9\varepsilon_{(i)}$$

Then ε_{*i} is a surrogate for ε_i, the effectiveness within the removed tenth of NCSS: ε_{*i} is called a pseudoestimate of ε_i.

Let
$$\bar{\varepsilon}_* = \left(\sum_1^{10} \varepsilon_{*i}\right) / 10$$
$$s^2 = \left(\sum_1^{10} (\varepsilon_{*i} - \bar{\varepsilon}_*)^2\right) / 9$$

Then $s^2/10$ is an approximation to the variance of the effectiveness using all of NCSS. It is called a jackknife estimate of variance.

A slightly different jackknife will be used here. Recall the effectiveness, $\mathcal{E}$, is a ratio of ratios. It has some undesirable properties: above all, it has a skewed sampling distribution. The literature suggests that, rather than jackknifing the ratio directly, it is better to separately jackknife the numerators and denominators of $\mathcal{E}$[53].

Specifically it was estimated, using all 35,610 (weighted) cases on NCSS and controlling for PDOF, age and belt usage, that x = 1185.32 drivers would have been injured if all cars were pre-Standard and y = 730.27 if all cars were post-Standard (see the derivation of R^- and R^+ at the end of Section 5.2.4). The effectiveness estimate was based on these 2 quantities x and y alone, viz.,

$$\mathcal{E} = 1 - \frac{y}{x} = 1 - \frac{730.27}{1185.32} = 38.4\%$$

The analogous quantities $x_{(i)}$ and $y_{(i)}$ will now be estimated for the various nine-tenths of the NCSS file. The estimates are shown in the 2nd and 3rd columns of Table 5-27 and are based on the tables in Appendix B. They were obtained as follows: the (raw unweighted) NCSS cases of drivers in frontal towaways were numbered consecutively in the order they appeared on the original NCSS file. (The original NCSS file was not ordered according to any periodic scheme, so it is reasonable to take systematic random samples.) For the calculation of $x_{(i)}$ and $y_{(i)}$, where i is an integer between 0 and 9, the cases whose identification number ends with the digit i were removed. The remaining cases, which constitute 9/10 of the NCSS

TABLE 5-27

ESTIMATES AND PSEUDOESTIMATES OF NUMBERS OF FATAL OR HOSPITALIZING INJURIES ASSUMING ALL CARS ARE PRE-STANDARD AND POST-STANDARD, FOR JACKKNIFE PROCEDURE IN WHICH TENTHS OF NCSS ARE REMOVED

All NCSS Cases except those with Case Id Ending in	Estimated Number of Injuries* Assuming All Cars Are		Only Those NCSS Cases with Case ID Ending in	Pseudoestimate of Number of Injuries Assuming All Cars Are	
	Pre-Standard	Post Standard		Pre-Standard	Post-Standard
	$x_{(i)}$	$y_{(i)}$		$x_{*i} = 1185.32 - x_{(i)}$	$y_{*i} = 730.27 - y_{(i)}$
1	1076.40	651.49	1	108.92	78.78
2	1062.55	653.71	2	122.77	76.56
3	1085.07	664.45	3	100.25	65.82
4	1054.22	660.93	4	131.10	69.34
5	1051.73	660.53	5	133.59	69.74
6	1066.36	649.74	6	118.96	80.53
7	1092.33	657.57	7	92.99	72.70
8	1086.82	646.10	8	98.50	84.17
9	1080.67	673.47	9	104.65	56.80
0	986.71	657.99	0	198.61	72.28

*Controlling for team, PDOF and age

frontal towaway driver file, were cross-classified by pre-post, injury, NCSS team, PDOF and driver age, precisely as was done for the full NCSS frontal towaway driver file in Step 18 of Section 5.2.4. The table was smoothed using the same model that was used in Step 19. The "estimated number of injuries assuming all cars are pre-Standard" was calculated from the table of expected cell entries, just as in Steps 20 and 21. This is $x_{(i)}$. A similar calculation yields $y_{(i)}$, the "estimated number of injuries assuming all cars are post-Standard."

The next task is to obtain the pseudoestimates x_{*i} and y_{*i} of the number of injuries that would have occurred in the removed tenth of NCSS consisting of cases ending in the digit i, assuming all cars are pre-Standard, or post-Standard, respectively. Since x_{*i} and y_{*i} are totals rather than rates,

$$x_{*i} = x - x_{(i)} = 1185.32 - x_{(i)}$$

$$y_{*i} = y - y_{(i)} = 730.27 - y_{(i)}$$

The 10 values of x_{*i} and y_{*i} are shown in the 5th and 6th columns of Table 5-27. These values are used to calculate:

$$x_* = \sum_{1}^{10} x_{*i} = 1210.3$$

$$y_* = \sum_{1}^{10} y_{*i} = 726.7$$

$$S_x = \left(\frac{10 \sum_{1}^{10} x_{*i}^2 - x_*^2}{9}\right)^{1/2} = 96.77$$

$$S_y = \left(\frac{10 \sum_{1}^{10} y_{*i}^2 - y_*^2}{9}\right)^{1/2} = 25.04$$

Let X be the number of injuries that would have occurred among an arbitrary sample of frontal-towaway-involved drivers of the same size as NCSS, using the same sampling scheme, and assuming all cars on the road were pre-Standard. The principal idea of the jackknife procedure is that $(X - x_*)/s_x$ is well approximated by a t distribution with 9 degrees of freedom.

Similarly, let Y be the number of injuries among an arbitrary NCSS-style sample, assuming all cars are post-Standard. $(Y - y_*)/s_y$ is approximately t distributed with 9 degrees of freedom.

The <u>effectiveness</u>

$$E = (1 - \frac{Y}{X})\ \%$$

is the ratio of 2 t distributions with 9 df each, several times multiplied by and subtracted from a constant.

A lower confidence bound for E (one-sided $\alpha = .05$) is obtained by solving:

$$-1.833 = \frac{y_* - \theta x_*}{(s_y{}^2 + (\theta s_x)^2)^{1/2}}$$

$$E = (1 - \theta)\%$$

In other words, the lower confidence bound for effectiveness is 28 percent.

An upper confidence bound for E is obtained by solving:

$$+1.833 = \frac{y_* - \theta x_*}{(s_y{}^2 + (\theta s_x)^2)^{1/2}}$$

$$E = (1 - \theta)\ \%$$

The upper confidence bound for effectiveness is 48 percent. These are the confidence bounds reported in Table 5-11, Section 5.2.3.

The use of one-sided confidence bounds with $\alpha = .05$ follows the practice established in NHTSA's Restraint Systems Evaluation Project [68] and Evaluation of Standard 214 [37]. The formula for the confidence bounds is derived from [40], pp. 125-6.

The null hypothesis that the effectiveness is zero can be tested by computing

$$\frac{y* - x*}{(s_y^2 + s_x^2)^{1/2}} = -4.84$$

If the null hypothesis were true, the above quantity would be an observation from a t distribution with 9df. Since the observed value of -4.84 is in the critical region of that distribution ($\alpha = .05$), the null hypothesis is rejected. Effectiveness is significantly greater than zero.

The annual nationwide benefits, B, of Standards 203 and 204 were estimated in Section 5.2.4 by the formula:

$$B = 28{,}411\ (\ (X - Y)\ \frac{1}{F}\ \frac{1}{1-U}\ \frac{1}{T}\ )$$

where 28,411 = number of passenger car fatalities in 1978 (FARS)

F = number of passenger car fatalities with known crash mode in a NCSS-style sample

U = fraction of fatal or hospitalizing driver injuries in frontal towaways with unknown contact point in NCSS data

T = fraction of fatal or hospitalizing passenger car driver injuries that occur in towaways in Oakland County, Michigan data.

The rel-variance of the benefits $V^2(B)$, the variance divided by the square of the benefits is readily approximated using the Taylor series expansion:

$$V^2(B) \cong \frac{(s_x^2 + s_y^2)}{(x_* - y_x)^2} + \frac{Var(F)}{F^2} + \frac{Var(U)}{(1-U)^2} + \frac{Var(T)}{T^2}$$

After substituting the values used in this section and the preceding one:

$$V^2(B) \cong .0427 + \frac{1}{873} + \frac{679}{1618 \cdot 2297} + \frac{215}{1414 \cdot 1629}$$

$$= .0427 + .0011 + .0002 + .0001$$

$$= .0441$$

Thus, the standard deviation of the benefits, S_B, is:

$$S_B = \sqrt{.0441}\ \hat{B} = 5082$$

Note that the contributions of F, 1–U and T to $V^2(B)$ were several orders of magnitude smaller than the contribution from X – Y. As a result, $(B - \hat{B})/S_B$ has, for all practical purposes, the t distribution with 9 df. The lower confidence bound for benefits (one-sided $\alpha = .05$) is:

$$\hat{B} - 1.833\ S_B = 14,900$$

The upper confidence bound for benefits is

$$\hat{B} + 1.833\ S_B = 33,500$$

Thus, based on NCSS data, it is estimated that Standards 203 and 204 would prevent between 14,900 and 33,500 fatal or hospitalizing steering assembly contact injuries per year if all passenger cars on the road were in compliance.

The null hypothesis that benefits are zero can be tested by computing $\hat{B}/S_B = 4.76$. Since this quantity is within the critical region ($\alpha = .05$) of a t distribution with 9 df, the null hypothesis is rejected. The benefits are significantly greater than zero.

The results obtained from the jackknife procedure were checked by estimating error with a more conservative approach: the 7 NCSS team sites were treated as clusters selected at random from the United States. Effectiveness of Standards 203 and 204 was measured separately using each team's data. The mean and standard error were computed for the 7 effectiveness estimates, weighted by the number of pre-Standard frontal crashes investigated by the team.

The resultant estimate of sampling error is conservative because the 7 NCSS sites were not selected at random, but were deliberately chosen to maximize geographic and demographic team-to-team variation. In other words, the NCSS team-to-team variation, for many statistics, could be expected to exceed the variation for 7 randomly selected clusters.

Table 5-28 shows the observed effectiveness of Standards 203 and 204 and the number of pre-Standard frontal NCSS cases for each team. In this context, "effectiveness" is merely

$$1 - \frac{\text{post-Std. injury rate}}{\text{pre-Std. injury rate}}$$

Since the number of post-Standard cases is relatively large, the variability of effectiveness is largely due to the pre-Standard injury rate. Thus, the number of pre-Standard cases is an appropriate weight factor for computing standard deviations. The negative effectiveness observed in the Highway Safety Research Institute cases is statistically quite compatible with the other teams' positive values, in view of the small pre-Standard sample obtained by HSRI.

TABLE 5-28

EFFECTIVENESS OF STANDARDS 203 AND 204, BY TEAM, NCSS

Team	Observed Effectiveness (%)	N of Pre-Standard Cases
Calspan	31	177
Highway Safety Research Institute	-2	189
U of Indiana	60	367
U of Kentucky	23	462
U of Miami	40	580
Southwest Research Institute	38	1531
Dynamic Science	69	645

The weighted average $\bar{\mathcal{E}}$ of the 7 effectiveness figures is 41.4 percent (it is biased upward by 3 percent because it was not adjusted for PDOF and driver age). The standard deviation s is 17.2. If E is the actual effectiveness of Standards 203 and 204 then $(E - \bar{\mathcal{E}}) / (s/\sqrt{7})$ is approximated by a t distribution with 6 degrees of freedom.

The lower confidence bound for effectiveness is

$$\bar{\mathcal{E}} - 1.943 \; s/\sqrt{7} = 29\%$$

The upper bound is

$$\bar{\mathcal{E}} + 1.943 \; s/\sqrt{7} = 54\%$$

The lower and upper bounds are both somewhat overstated because $\bar{\mathcal{E}}$ somewhat overstates the effectiveness and because the sampling distribution of E was assumed symmetric when , in fact, it is skewed to the left.

The important finding, however, is that the width of the confidence bounds, by this deliberately conservative estimation method, is 25 (i.e., from 29 to 54). This is just moderately larger than the width obtained by the jackknife procedure, which was 20 (from 28 to 48). The implications are that

- The jackknife procedure resulted in valid confidence bounds for effectiveness of Standards 203 and 204 within the NCSS sites.
- The effectiveness of Standards 203 and 204 is relatively insensitive to site-to-site variation; as a result, the NCSS estimate is probably a good national estimate as well.

5.3 Analysis of Fatal Accident Reporting System data

The Fatal Accident Reporting System (FARS) contains a virtual census of the fatalities that have occurred since January 1, 1975. As of January 1980, FARS contained over 125,000 passenger car occupant fatalities, versus approximately 900 on NCSS. Given suitable analysis techniques, FARS has the potential to provide more reliable results on fatality reduction than NCSS.

Analytic techniques were developed to estimate the fatality reduction attributable to Standards 203 and 204. It was found that the Standards reduce the driver's fatality risk in frontal crashes by 12.1 percent,which would correspond to annual prevention of 1300 fatalities if all passenger cars complied with the Standards. As will be described below, these findings are comparable to the NCSS results.

5.3.1 Method

There are some difficulties in using FARS data. Since FARS only contains fatal accidents, it is not possible to compute fatality rates per 100 (fatal or nonfatal) crash involved drivers. So it is not possible to directly compare the driver fatality rates of pre- and post-Standard cars. FARS is based on State data and contains less detailed information than NCSS: it is not possible to determine whether a fatality was caused by steering assembly contact. FARS does, however, permit distinction between frontal and nonfrontal impacts, based on damage location.

FARS is best used to compute indirectly the relative fatality risk of pre- and post-Standard cars: the driver fatalities in frontal impacts are compared to a control group of fatalities unaffected by Standards 203 and 204. Moreover the driver frontals and the control group should be similar - i.e., subject to the same influence, if any, by other safety factors - except for the effect of Standards 203 and 204. The fatalties are then tabulated by pre/post, for the control group and the driver frontals:

FATALITIES	control group	driver frontals
pre-Standard cars	n_{11}	n_{12}
post-Standard cars	n_{21}	n_{22}

The ratio n_{21} / n_{11} is an indirect measure of the likelihood of post-Standard car fatalities relative to pre-Standard. It takes into account the differences of exposure and the effects of other Standards. If Standards 203 and 204 had no effect on driver frontals, the expected number of driver frontal fatalities in post-Standard cars would be $n_{12}\ (n_{21} / n_{11})$. Thus,

$$\varepsilon = (1 - \frac{n_{22} \cdot n_{11}}{n_{12} \cdot n_{21}})\%$$

is a measure of the effectiveness of Standards 203 and 204 in reducing driver frontal fatalities. Furthermore, if the ordinary Chi-square statistic for the above table is in the critical region of the Chi-square distribution with 1df, the hypothesis that the Standards had no effect is rejected.

Specifically fatality counts for model years 1966 (pre-Standard) and 1968 (post-Standard) were used. There were 2 alternative control groups:

(1) Passenger fatalities in frontal impacts

(2) Driver fatalities in side and rear impacts.

Effectiveness was calculated using each control group and the results were averaged.

The data were limited to model years 1966 and 1968 for the following reasons:

- By removing all the older and newer vehicles, "age effects" and design changes that might affect the control group differently from the driver frontals are minimized.

- By 1966, all cars were equipped with windshields and door locks capable of meeting Standards 205 and 206.

- No cars were equipped with side door beams (Standard 214) before 1969.

- Model year 1967 is removed because some manufacturers met Standards 203 and 204 while others didn't (See Table 3-12). Retention of this group would create differences in the pre- and post-Standard populations.

The tabulations were based on the 1975-79 FARS data that were on file on December 31, 1979. At that time, the 1979 file was approximately 75 percent complete. Specifically, the "frontal" impacts were those whose "principal impact point" was 11, 12 or 1 o'clock. The "side and rear" impacts had principal impact point 2 - 10 o'clock.

5.3.2 Results

Table 5-29 compares the driver and passenger fatalities in frontal impacts. Based on the trend in passenger fatalities, (1463/1048) 2119 = 2958 frontal driver fatalities were expected in the post-Standard cars. In fact, only 2573 occurred. This is a statistically significant 13 percent reduction.

Table 5-30 compares the driver frontal fatalities to the driver fatalities in side and rear impacts. Based on the trend in the latter, (1508/1103)2119 = 2897 frontal fatals are expected. Since only 2573 occurred, a statistically significant 11.1 percent reduction took place.

The results with the 2 alternative control groups (13% and 11.1%) are obviously compatible, given the sample sizes under consideration. A single "best estimate" was obtained by comparing the observed frontal driver fatalities (2573) to the average of the "expected" fataltiies as computed by the 2 techniques (2958 and 2897). This yields an estimated fatality reduction of 12.1 percent.

These results were checked for possible anomalies in 1966 or 1968 cars by repeating the analyses with the 1965 and 1969 models included. The fatality counts are shown in Tables 5-31 and 5-32. The inclusion of these model years somewhat "contaminates" the analyses because they overlap with the implementation of Standard 205 which helped passengers more than drivers and Standard 214 which affects sidedoor impacts. Thus, a small reduction in the effectiveness estimate for Standards 203 and 204 may occur because the control group is helped by the other Standards. The fatality counts in Tables 5-31 (drivers versus passengers) and 5-32 (frontals versus side/rear) both indicate a statistically significant 11.0 percent reduction in frontal driver fatalities relative to the control group. This is 1.1

TABLE 5-29

PASSENGER AND DRIVER FATALITIES IN FRONTAL IMPACTS OF 1966 AND 1968 PASSENGER CARS, FARS 1975-79

	Passengers	Drivers
Model year 1966	1048	2119
Model year 1968	1463	2573

Chi-square = 7.79 (p = .005)

TABLE 5-30

DRIVER FATALITIES IN SIDE/REAR AND FRONTAL IMPACTS OF 1966 AND 1968 PASSENGER CARS, FARS 1975-79

	Side/Rear	Frontal
Model year 1966	1103	2119
Model year 1968	1508	2573

Chi-square = 5.83 (p = .016)

TABLE 5-31

PASSENGER AND DRIVER FATALITIES IN FRONTAL IMPACTS OF 1965-66 AND 1968-69 PASSENGER CARS, FARS 1975-79

	Passengers	Drivers
Model years 1965-66	1893	3793
Model years 1968-69	3094	5518

Chi-square = 10.17 (p = .001)

TABLE 5-32

DRIVER FATALITIES IN SIDE/REAR AND FRONTAL IMPACTS OF 1965-66 AND 1968-69 PASSENGER CARS, FARS 1975-79

	Side/Rear	Frontal
Model years 1965-66	1977	3793
Model years 1968-69	3233	5518

Chi-square = 10.86 (p = .001)

percent lower than the average of 12.1 percent obtained when only model years 1966 and 1968 were used. The results are compatible, considering the sample sizes on which they are based.

The benefits of Standards 203 and 204 are the total number of fatalities that the Standards would have prevented in 1978 if all cars on the road were in compliance. The benefits are the difference of D^-, the number of frontal driver fatalities that would have occurred if no cars had met the Standards and D^+, the number that would have happened if all cars complied. Now:

$$D^- = \left(f^- + \frac{f^+}{1-\mathcal{E}} \right) \frac{F_1}{F_2}$$

$$D^+ = \left((1-\mathcal{E}) f^- + f^+ \right) \frac{F_1}{F_2}$$

where:

f^- = pre-Standard frontal driver fatals, FARS 1978 = 1177

f^+ = post-Standard frontal driver fatals, FARS 1978 = 8212

$\mathcal{E}$ = effectiveness of Standards 203/204 = .121

F_1 = total passenger car fatalities on FARS 1978 = 28,411

F_2 = passenger car fatalities on FARS 1978 with known seat position and impact point = 27,338

Thus:

D^- = 10,932

D^+ = 9,610

Benefits = $D^- - D^+ \cong$ 1,300 lives saved annually.

The procedures for estimating benefits can also be used to estimate the magnitude of the problem – the number of fatalities that would have occurred in 1978 if Standards 203 and 204 had not been promulgated. The following procedure was used to obtain the estimates in Table 3-3:

(1) The number of driver fatalities in frontal crashes would have been

$$D^- = 10{,}932$$

(2) There were a total of 28,411 passenger car occupant fatalities in the 1978 FARS. The number that would have occurred if the Standards had not been promulgated is

$$28{,}411 + D^- - (f^- + f^+)\frac{F_1}{F_2} = 29{,}585$$

(3) There were 18,194 passenger car driver fatalities and 410 passenger car occupant fatalities with unknown driver/passenger role. The number of driver fatalities that would have occurred if the Standards had not been promulgated is

$$18{,}194\,\frac{28{,}411}{28{,}411 - 410} + D^- - (f^- + f^+)\frac{F_1}{F_2} = 19{,}569$$

5.3.3 Error Measurement

The FARS results were based on combining 5 calendar years of data (1975-79). Each of the individual calendar years of FARS is a subsample of the file that was used.

An empirical and conservative method for estimating the error of the FARS results is to perform the calculation of effectiveness and life-savings separately for each of the 5 calendar years of FARS and to examine the variation of the results.

Table 5-33 compares the driver and passenger fatalities in frontal impacts of 1966 and 1968 cars, by calendar year of FARS. It is identical to Table 5-29, except the data have been subdivided by calendar year of FARS.

Table 5-34 compares the driver and passenger fatalities in frontal impacts to the driver fatalities in side and rear impacts. It is analogous to Table 5-30, except the data have been subdivided by calendar year.

The calculation of effectiveness and benefits is performed separately for each calendar year of FARS, exactly as was done for the combined data files in Section 5.3.2. Table 5-35 summarizes the calculations.

For example, based on the trend in passenger fatalities in the 1975 FARS (Table 5-33), (354/332) 631 = 673 frontal driver fatalities were expected in the 1968 cars. Based on the trend in side/rear driver fatalities in the 1975 FARS (Table 5-34), (385/301) 631 = 807 frontal driver fatalities were expected. The average of the expected fatalities as computed by the 2 techniques (673 and 807) is 740. In fact, only 665 frontal driver fatals in 1968 cars were observed in the 1975 FARS. This yields a fatality reduction of 1-(665/740) = 10.1 percent. The benefits of Standard 203 and 204 are now calculated using the same formula and parameters as for the combined FARS data, except that the effectiveness value for the 1975 FARS is used. (Since the objective is to calculate potential benefits for base year 1978, it is necessary to use the census parameters for 1978 - e.g., 28,411 total passenger car fatalities - not 1975.)

TABLE 5-33

PASSENGER AND DRIVER FATALITIES IN FRONTAL IMPACTS OF 1966 AND 1968 PASSENGER CARS, FARS, BY CALENDAR YEAR

	FARS 1975		FARS 1976		FARS 1977		FARS 1978		FARS 1979	
	Psgrs.	Drivers	Psgrs.	Drivers	Psgrs.	Drivers	Psgrs.	Drivers	Psgrs.	Drivers
Model year 1966	332	631	250	539	200	412	165	329	101	208
Model year 1968	354	665	370	633	302	543	269	456	168	276

TABLE 5-34

DRIVER FATALITIES IN SIDE/REAR AND FRONTAL IMPACTS OF 1966 AND 1968 PASSENGER CARS, FARS, BY CALENDAR YEAR

	FARS 1975		FARS 1976		FARS 1977		FARS 1978		FARS 1979	
	Side/Rear	Frontal	Side/Rear	Frontal	Side/Rear	Frontal	Side/Rear	Frontal	Side/Rear	Frontal
Model year 1966	301	631	274	539	228	412	180	329	120	208
Model year 1968	385	665	374	633	310	543	267	456	172	276

TABLE 5-35

ESTIMATION OF EFFECTIVENESS AND BENEFITS OF STANDARDS 203 AND 204, FOR 5 CALENDAR YEARS OF FARS DATA

Calendar year	Driver Frontal Fatalities in 1968 Cars: Observed	Expected: Based on Psgr. Frontal Fats	Expected: Based on Driver Side/Rear Fats.	Average	Defined in Section 5.3.2: ε	D^-	D^+	Benefits
FARS 1975	665	673	807	740	10.1%	10,716	9634	1082
FARS 1976	633	798	736	767	17.5%	11,568	9543	2025
FARS 1977	543	622	560	591	8.1%	10,510	9658	852
FARS 1978	456	536	488	512	10.9%	10,802	9624	1178
FARS 1979	276	346	298	322	14.3%	11,182	9583	1599
				$\bar{x}$	12.2%			1347
				s	3.72			466
				$2.132\ s/\sqrt{5}$	3.55			444
			For 5 years combined	Lower Bound	8.6%			903
				Upper Bound	15.7%			1791

The calculation is repeated for each of the 5 calendar years of FARS. Table 5-35 shows that the estimates of effectiveness from the 5 subsamples ranged from 8.1 percent to 17.5 percent and the benefits ranged from 852 to 2025 lives saved.

Let $\mathcal{E}$ and b be the effectiveness and benefits calculated using 1 year of FARS data. Let $\mathcal{E}_i$ and b_i, respectively, be the effectiveness and benefits estimated using FARS data from calendar year i. Then

$$\bar{\mathcal{E}} = \sum_{1975}^{1979} \mathcal{E}_i / 5 = 12.2\%$$

$$s_{\mathcal{E}} = \left(\sum_{1975}^{1979} (\mathcal{E}_i - \bar{\mathcal{E}})^2 / 4 \right)^{1/2} = 3.72$$

$$\bar{b} = \sum_{1975}^{1979} b_i / 5 = 1347$$

$$s_b = \left(\sum_{1975}^{1979} (b_i - \bar{b})^2 / 4 \right)^{1/2} = 466$$

are the average effectiveness and benefits calculated from 1 year of FARS data and their standard deviations (calculated from the sample). Even though $\mathcal{E}$ and b are ratio estimates, the denominators involved in the ratios have fairly small coefficients of variation, so their distributions may be considered approximately normal.

Let E and B be the effectiveness and benefits of Standard 203 and 204 calculated using 5 years of FARS data. Then $(E - \bar{\mathcal{E}}) / (s_{\mathcal{E}} / \sqrt{5})$ and $(B - \bar{b}) / (s_b / \sqrt{5})$ are approximated by a t distribution with 4 degrees of freedom [53].

Thus, a lower confidence bound for effectiveness E (one-sided $\alpha = .05$) is given by

$$\bar{\mathcal{E}} - 2.132\, s_{\mathcal{E}} / \sqrt{5} = 8.6\%$$

driver frontal fatality reduction. The upper confidence bound for effectiveness is

$$\bar{\mathcal{E}} + 2.132\, s_{\mathcal{E}} / \sqrt{5} = 15.7\%$$

driver frontal fatality reduction.

The lower confidence bound for benefits is

$$\bar{b} - 2.132\, s_b / \sqrt{5} = 903$$

lives saved in a year. The upper bound for benefits is

$$\bar{b} + 2.132\, s_b / \sqrt{5} = 1791$$

lives saved in a year.

These confidence bounds were calculated by an empirical process and may be considered reliable. There are two caveats associated with the calculation: the estimators of effectiveness and benefits for the individual years involve ratios and deviate somewhat from normality – although the coefficients of variation of the denominators are relatively small. The 5 subsamples (5 years of FARS data) are not of equal size, but they have been weighted equally, for simplicity, in performing the calculations.

5.3.4 Comparison of FARS and NCSS results

The FARS results on fatality reduction are comparable to the NCSS findings on fatal or hospitalizing injury reduction. The NCSS analysis (Section 5.2) showed that the Standards resulted in an estimated 38 percent reduction of steering assemblycontact injury; 46 percent of the fatal or hospitalizing driver injuries in pre-Standard frontal impacts on the NCSS file involved steering assembly contact and no other serious injury contact (see Table 3.2 - it is unknwon, though, whether the same percentage would apply to fatalities). Thus, the Standards are responsible for an overall fatal-or-hospitalizing injury reduction of (.46) (.38) = 17.5 percent for drivers in frontal crashes, according to NCSS. This is somewhat higher than the 12.1 percent overall fatality reduction for drivers in frontal crashes found in FARS, although the difference of the effectiveness measurements is not statistically significant.

The Wilcoxon rank sum test ([10], p. 144) was used to compare the NCSS and FARS results: the overall FARS effectiveness (12.1%) can be construed as the average effectiveness over 5 years of FARS data. Thus, there are 5 observations from FARS, viz., the effectiveness for the individual years 1975-79 (which were 10.1, 17.5, 8.1, 10.9, and 14.3 according to Table 5-35). Ten observations can be obtained for the NCSS data by using the 10 pseudoestimates of pre-Standard injuries (x_{*i}) and post-Standard injuries (y_{*i}) from Table 5-27: the overall serious injury reduction due to Standards 203 and 204 in the ith tenth of NCSS is

$$\varepsilon_i = \frac{99}{214}\left(1 - \frac{y_{*i}}{x_{*i}}\right) \%$$

where 99/214 is the fraction of fatal or hospitalizing driver injuries in frontal crashes of pre-Standard cars which are primarily due to steering assembly contact (see Table 3-2). The resulting 10 observations from NCSS are 12.8, 17.4, 15.9, 21.8, 22.1, 14.9, 10.1, 6.7, 21.1 and 29.4. The 5 FARS and 10 NCSS observations are pooled and ranked 1-15 from lowest to highest (using the mean of the tied ranks for each of two tied observations). The sum of the ranks for the 5 FARS observations is 28.5. Since this value is within the acceptance region for the Wilcoxon rank sum test with 5 and 10 observations, respectively, the null hypothesis that the fatality reduction in FARS equals the serious injury reduction in NCSS is not rejected.

Although the observed difference between the fatality and injury reduction is not statistically significant, it is not counterintuitive either. There are several reasons why the fatality reduction due to Standards 203 and 204 might be somewhat lower than the injury reduction:

(1) Fatal frontal accidents are relatively more likely to involve massive multiple injury sources, gross intrusion of the frontal structure, ejection or external object intrusion. Nonfatal injury accidents are more likely to involve simple contact with the steering assembly with few other complications.

(2) The steering wheel improvements that manufacturers made voluntarily at the time that Standards 203 and 204 took effect (see Section 3.4.3) appear to have been quite effective in reducing nonfatal injury but probably had less effect on fatalities (see Sections 6.3.2 and 6.10).

5.4 Cost effectiveness of Standards 203 and 204

One of the evaluation objectives was to determine whether Standards 203 and 204 are cost-effective.

The consumer cost of Standards 203 and 204 was estimated in Chapter 4. The 2 sources of cost were the hardware added or modified in response to the Standards and the additional lifetime fuel consumption due to weight added to cars by the Standards. The total consumer cost, which included voluntary hardware improvements as well as those required for meeting the compliance tests, was $10.46 per car. Since about 10 million passenger cars are sold annually in the United States, the total cost of Standards 203 and 204 is $104.6 million per year.

The benefits of Standards 203 and 204 are lives saved and serious injuries prevented. It was estimated from FARS (Table 5-35) that the Standards will prevent 1347 $\pm$ 444 fatalities annually when all passenger cars are in compliance. The NCSS data provided an estimate of 24221 $\pm$ 9315 fatal or serious injuries prevented (Section 5.2.5). These estimates included the effects of voluntary steering assembly improvements that coincided with the Standards.

Benefits can also be expressed in Equivalent Fatality Units (EFU). The concept was defined and used in NHTSA's evaluation of Standard 214 [37]. Each life saved by Standards 203 and 204 is a benefit of 1 EFU. Each person who avoids nonfatal hospitalizing steering assembly contact injury is assigned a benefit of 0.05 EFU. This assignment of EFU is based on an assessment of average cost of nonfatal injuries requiring hospitalization [19].

The concept of equivalent fatality units is useful for expressing, in a single figure, the cost-effectiveness of a standard that saves lives and prevents injuries. What is that single figure for Standards 203 and 204? The FARS estimate of 1347 lives saved contributes 1347 EFU's. The NCSS benefits were 24,211 fatal or hospitalizing steering assembly contact injuries. It is necessary to subtract the fatality prevention (1347 from FARS) to obtain the number of nonfatal hospitalizing injuries prevented: 22,874. Each of these contributes 0.05 EFU, so the contribution from nonfatal injuries is 1144 EFU. Thus, the total benefits of Standards 203 and 204 are 2491 EFU.

The confidence bounds for EFU's eliminated by the Standards can be calculated by noting that both the FARS and NCSS estimates are drawn from t-distributions (after subtracting the mean and dividing by the standard deviation). Let

b_f = lives saved = 1347

b_n = nonfatal injuries prevented = 22874

b = total EFU's eliminated = $b_f + 0.05\, b_n$ = 2491

s_f = standard deviation of $b_f = \frac{466}{\sqrt{5}}$ (from Table 5-35) = 208

d_f = degrees of freedom for FARS estimate = 4

s_n = standard deviation of b_n = 5082 (from Section 5.2.5)

d_n = degrees of freedom for NCSS estimate = 9

Now let

s = standard deviation of $b = (s_f^{\,2} + (.05\, s_n)^2)^{1/2} = 328$

d = degrees of freedom for b (See [10], p. 136)

$= s^4 / (s_f^{\,4} / d_f + (.05\, s_n)^4/d_n)$

$= 12$

Thus the total benefits of Standards 203 and 204, expressed in EFU, are approximately t distributed with 12 degrees of freedom (after subtracting the mean and dividing by the standard deviation). A lower confidence bound for benefits (one-sided α =.05) is given by

$b - 1.782\ s = 1907$ EFU

An upper bound for benefits is given by

$b + 1.782\ s = 3075$ EFU

The <u>cost-effectiveness</u> of Standards 203 and 204 is expressed, in this evaluation, as the number of <u>EFU's eliminated per million dollars of cost</u>. Since the Standards eliminate 2491 EFU and cost $104.6 million per year, the cost effectiveness is

$$\frac{2491}{104.6} = 23.8 \text{ EFU per million dollars}$$

A lower confidence bound for cost-effectiveness (one-sided $\alpha = .05$) is given by

$$\frac{1907}{104.6} = 18.2 \text{ EFU per million dollars}$$

The upper bound is

$$\frac{3075}{104.6} = 29.4 \text{ EFU per million dollars}$$

The cost-effectiveness of Standards 203 and 204 obviously compares very favorably with most public safety and health programs.

For comparison, Standard 214 - Side Door Strength - has been evaluated by NHTSA and found to be cost-effective [37]. It was estimated to eliminate 5.3 EFU per million dollars of cost, with a confidence range of 2.7 to 7.9. (Benefits of Standard 214 are based on AIS $\geq$ 3 reduction in single vehicle crashes - [37], p. 158 - and have been converted to EFU — p. 160. Cost was increased by 7 percent to convert from 1977 to 1978 dollars.)

5.5 Summary of effectiveness results

There is remarkable agreement between 8 studies on the effectiveness of Standard 203 and 204. All of them show statistically significant effectiveness of approximately the same magnitude. The 8 studies include the NCSS and FARS analyses performed for this evaluation, 3 other studies based on investigator collected data [45], [56], [62] and 3 analyses of police-collected data [44], [50], [58]. Table 5-36 summarizes the methods, criteria and results of the 8 analyses. Another study [5], reviewed in Section 5.1.3, is not included in the summary because it was suspected of serious biases: the pre-Standard and post-Standard cars largely came from 2 different, statistically incompatible data files.

Two measures of effectiveness were obtained: reduction of steering assembly contact injury could be measured in studies based on investigator-collected data. Overall driver injury reduction in frontal crashes was found using police-reported data. Both measures were obtained in NCSS - since 46.3 percent of the driver hospitalizations in frontal crashes were primarily due to steering assembly contact, the 38 percent effectiveness by the first measure corresponds to an 18 percent effectiveness by the second measure.

The results on steering assembly contact injury reduction varied from 27 percent to 54 percent with the NCSS results in the middle at 38 percent. The variation in the results of the other 3 studies could easily be due to chance, since they were based on smaller samples than NCSS and the confidence bounds for the NCSS results were from 28 to 48 percent. The ACIR study may have found lower effectiveness, in part, because minor injuries were included in the analysis. The two MDAI studies may have found higher effectiveness, perhaps, because of the characteristics of their non-probability samples. At any rate, considering the sample sizes on which the studies are based, the results are highly consistent.

The results on overall reduction of driver injury in frontal crashes range from 12 percent to 24 percent. That range is consistent with the one for steering assembly contact injury reduction because in NCSS just under half of the driver injuries in frontal crashes were due to steering assembly contact. The lowest estimate of effectiveness (12 percent) came

TABLE 5-36

SUMMARY OF 8 EFFECTIVENESS STUDIES OF STANDARDS 203 AND 204

	Data Source	Population Studied	Injury Criterion	Steering Contact Injury Reduction (%)	Overall Frontal Driver Inj. Red. (%)	Stat. Sig.?
1.	NCSS 1977-79	Frontal and angle-frontal; Pre vs. post std; Adj. for confounding effects	Fatal or hospitalizing	38	18	Yes
2.	FARS 1975-79	Frontal and angle frontal crashes; MY 66 vs. MY 68; Fat. risk rel. to control group	Fatality		12	Yes
3.	ACIR 1964-69	MY 64-66 vs.post Std.; GM cars only	Any torso inj.	32		Yes
			Any head inj.	27		Yes
4.	MDAI - Los Angeles 1962-69	MY 60-66 vs. MY 67-68; crashes with at least 1 AIS ≥ 2; Inj. risk rel. to non-steering injuries	AIS ≥ 2	54		Yes
5.	MDAI - Michigan and Los Angeles	Pre vs. Post Standard; crashes with high frontal Delta V and steering contact	AIS ≥ 3	45		Yes
6.	North Carolina State 1966 & 1968	Pre Std. vs. Post Standard; No cars older than MY 64; car-to-car crashes	K + A		14	Yes
7.	North Carolina State 1971-72	Pre Std. vs. Post Std.; Front-to-Front and Front-to-Rear 2 car collisions	K + A		20	Yes
8.	New York State	Last Pre-Std MY vs. First Post-Std.; Head-on car-to-car crashes only	K + A		24	Yes

from FARS, which used the most conservative appraoch: driver fatalities in frontal crashes were compared to control groups of fatalities not affected by Standards 203 and 204. FARS also used a different injury criterion, viz., fatals only. The NCSS result was again in the middle – 18 percent – and was statistically compatible with FARS (See Section 5.3.4). The slightly higher effectiveness observed in the second North Carolina study and in New York may be due to chance alone – the sample sizes were relatively small – or perhaps it occurred because these studies presented straightforward comparisons of injury rates without attempting to control for the effects of standards other than 203 and 204 or for other differences between the pre- and post-Standard cars.

CHAPTER 6

SPECIFIC QUESTIONS CONCERNING THE EFFECTIVENESS OF STANDARDS 203 AND 204

The preceding chapter presented the evidence that Standards 203 and 204 are effective and that they will annually prevent an estimated 1300 deaths and 23,000 serious nonfatal injuries when all cars will be in compliance. But it did not address why the standards are effective nor, for that matter, why they are not more effective.

The "why" questions will be addressed here. The approach will be to reexamine one-by-one the issues originally raised in Chapter 3 - in the sections that defined the problem (3.1 - 3.3), described the hardware modifications (3.4) and discussed engineers' concerns regarding effectiveness (3.5). The actual experience with post-Standard cars will be analyzed to determine how effective the Standards have been in alleviating specific problems and accomplishing their intended goals. Finally, the results on specific questions will be compared in order to obtain an overall judgment of why the Standards have been effective.

The specific issues that will be examined in this chapter are:

- Intrusion reduction due to Standard 204
- Effectiveness of alternative energy absorbing devices
- Injury reduction by body region
- Secondary effect of the Standards - potentially more windshield and instrument panel injuries
- Binding of the column EAD
- Effectiveness as a function of PDOF

- Effectiveness as a function of Delta V
- Effectiveness as a function of damage location
- Effectiveness as a function of crash type, vehicle weight, driver age, sex and belt usage

National Crash Severity Study (NCSS) data are analyzed throughout the chapter. The effectiveness values and injury rates in this chapter are based on simple weighted NCSS data counts and do not involve the modeling and adjustment process developed in Section 5.2.4. Most of the analyses of this chapter involve subsamples of NCSS which are too small for effective use of the modeling and adjustment process. That process, however, caused relatively little net change in effectiveness (starting with a simple effectiveness of 34 percent, controlling for "team" raised it to 42 percent but controlling for other variables dropped it back down to 38 percent). So nonuse of the process probably did not substantially bias the results of this chapter.

6.1 Intrusion reduction due to Standard 204

Perhaps the most serious shortcoming of the pre-Standard steering assembly was the danger of column intrusion into the passenger compartment (see Section 3.2). Column intrusion occurred in 3.5 percent of the pre-Standard frontal towaway crashes on the National Crash Severity Study (NCSS) file. Yet this fairly small number of crashes produced 20 percent of the steering contact injuries (fatal or requiring hospitalization) and 27 percent of the AIS ≥ 3 steering injuries that resulted in death or hospitalization (see Tables 3-5 and 3-6).

A large portion of the steering assembly research and development was devoted to intrusion reduction (Section 3.4). The problem was considered important enough to require a Federal Motor Vehicle Safety Standard of its own - Standard 204.

The compliance test for Standard 204 specifies that rearward column intrusion shall not exceed 5 inches at any time during a 30 mph frontal barrier impact.

A small number of pre-Standard cars were subjected to the compliance test and failed it completely - the steering columns intruded clear through the driver's normal seating space [41]. Since 1968, many post-Standard cars have been tested for compliance and there have been only 4 failures, which occurred in models accounting for well under 1 percent of the automobiles sold in the United States. No failure occurred after 1971.

The performance of Standard 204 in actual highway accidents is nearly as good as the compliance tests results. Table 6-1 shows that the post-Standard cars had a 68 percent lower incidence of steering column intrusion in frontal crashes than the pre-Standard cars. The difference of column intrusion rates is statistically significant ($z = 12.03$ with weighted NCSS cases; $p < .01$ even after adjusting for the NCSS sampling plan). By contrast, Table 6-1 shows that the intrusion rates for components <u>other than</u> the steering column is about the same for pre-Standard 204 and post-Standard cars. In other words, vehicle design changes of the past 15 years, other than Standard 204, do not appear to have had much effect, if any, on intrusion in frontal crashes. Thus, the large reduction in column intrusion is due, specifically, to the hardware installed in response to Standard 204.

Standard 204 has resulted in a reduction of intrusion in frontal crashes at all severity levels. Table 6-2 shows that column intrusion was reduced by 88 percent in the low-speed crashes with Delta V in the 1-14 mph range. In the more severe 15-29 mph Delta V crashes, the reduction was 62 percent. Even in the most severe

TABLE 6-1

STEERING COLUMN INTRUSION REDUCTION
DUE TO STANDARD 204, NCSS FRONTAL CRASHES

	Pre-Standard Cars	Post-Standard Cars
Percent with column intrusion	3.47	1.11
COLUMN INTRUSION REDUCTION	→	68%
N of cases	3951	31,659
Percent with other, unspecified, or catastrophic intrusion	8.88	9.39

TABLE 6-2

STEERING COLUMN INTRUSION REDUCTION DUE TO
STANDARD 204, BY DELTA V,
NCSS FRONTAL CRASHES

	Delta V (mph)			
	1-14	15-29	30+	Unknown
Pre-Standard % with column intrusion	1.45	6.84	23.6	2.29
Post-Standard % with column intrusion	0.17	2.59	14.3	0.84
Intrusion reduction for Standard 204	88%	62%	39%	64%

group of crashes - the ones in which the Delta V equalled or exceeded the compliance test speed of 30 mph - there was a substantial 39 percent intrusion reduction.

The definition of "column intrusion," as used above, is any displacement of the steering wheel into the passenger compartment at final rest - rearward, upward, downward or sideways - of one inch or more. Standard 204, however, only specifies limits on rearward intrusion. Engineers expressed concern that the hardware installed in response to the Standard, while effective against rearward intrusion, would not prevent upward and sideways intrusion (see Section 3.5). They were also concerned that this type of intrusion constituted a safety hazard.

Analysis of 41 Standard 204 compliance test films showed that vertical intrusion was common in the 30 mph barrier crashes, but was generally limited to a few inches [31]. There were a few makes and models - small imported cars with a series of universal joints in the engine compartment section of the column - in which more extensive vertical intrusion up to 10 inches occurred. The vertical intrusion in the 41 tests was distributed about equally between upward and downward movement. The columns tended to oscillate - i.e., the final rest position of the steering wheel was not necessarily indicative of the maximum intrusion that occurred during the crash phase.

The NCSS cases collected after March 1978 contain measurements of the primary direction of intrusion (rearward, vertical or lateral) and the number of inches of intrusion at final rest. Of course, the NCSS investigators had no way to measure oscillations of the column prior to final rest. The "primary" axis of intrusion is the one which comes closest to the actual intrusion vector. For example, a simple displacement of the column without changing its mounting angle is primarily a "rearward intrusion," even though the movement contains a smaller upward component.

These later NCSS data confirm the engineers' concern that Standard 204 is only effective against primary rearward column intrusion. Table 6-3 shows that rearward intrusion occurred in 4.58 percent of the pre-Standard cars but only in 0.85 percent of the post-Standard cars. This is a significant 81 percent reduction. On the other hand, primary vertical or lateral intrusion was observed in 0.46 percent of the pre-Standard vehicles and in 0.77 percent of the post-Standard vehicles. These rates are not significantly different. Standard 204 has been so effective in reducing rearward column movement that close to half of the post-Standard intrusion cases involve primarily vertical or lateral movement. Small imported cars are not overrepresented among the vertical/lateral intrusion cases: they only account for 3 of the 98 (weighted) NCSS cases (see Appendix C).

Table 6-4 shows that 4 percent of the post-Standard car drivers with fatal or hospitalizing steering contact injury were in cars with measurable vertical or lateral intrusion. The direct contribution of vertical intrusion to injury in post-Standard cars is small relative to rearward intrusion in pre-Standard cars, but it is not negligible. Moreover, the NCSS results do not preclude the possibility that small vertical column oscillations - which do not result in measurable vertical intrusion at rest - may be a factor in causing the column to bind prior to driver contact with the steering wheel.

The NCSS data show that Standard 204 has been highly successful in achieving a reduction of rearward column intrusion in highway accidents. The next logical question is: to what extent is the effectiveness of the combined Standards 203 and 204 (estimated to be 38 percent in Chapter 5) attributable to intrusion reduction alone? It is, of course, impossible to isolate precisely the individual benefit of one hardware improvement from the benefits of other hardware that was installed at the same time. But NCSS does allow a rough estimate.

TABLE 6-3

STEERING COLUMN INTRUSION REDUCTION DUE TO STANDARD 204, BY DIRECTION OF COLUMN MOVEMENT, FRONTAL CRASHES, NCSS, POST-MARCH 1978

	Percent with Intrusion		Reduction for
	Pre-Standard	Post-Standard	Post-Standard
Rearward intrusion	4.58	0.85	81%
Upward, downward or sideways intrusion	0.46*	0.77	-68%
N of cases	1092	12,747	

* rate is based on only 5 weighted NCSS cases

TABLE 6-4

COLUMN INTRUSION INVOLVEMENT IN FATAL OR HOSPITALIZING STEERING CONTACT INJURIES, NCSS, POST-MARCH 1978

	Pre-Standard Cars	Post-Standard Cars
Percent with rearward intrusion	18	6
Percent with vertical or sideways intrusion	3	4
Percent in catastrophic crashes	3	6
Percent with no column intrusion	76	84
N of injured drivers	34	360

Intrusion was associated with 20 percent of the pre-Standard steering contact injuries (Table 3-6) and a higher percentage of the fatalities and more serious injuries. Standard 204 reduced intrusion by 68 percent (Table 6-1). Thus, it is possible that up to 14 percent of the steering contact injuries were eliminated by the intrusion reduction. Since the effectiveness of the combined standards was 38 percent, it would seem that between 1/3 and 1/2 of the overall injury reduction and an even higher fraction of the fatality reduction is due to intrusion reduction.

6.2 Comparative effectiveness of alternative energy absorbing devices

Initially, GM, AMC and Chrysler used a mesh-type energy absorbing column and Ford installed the basically similar slotted column (see Section 3.4.3). When GM employed a substantially different design - the ball column - in their 1969 models, it became reasonable to inquire whether one design was more effective than another.

6.2.1 Earlier comparative studies

Indeed, Marquis and Rasmussen (GM engineers) suggested that the ball column was introduced, in part, because it was considered possibly more effective than the mesh type [48], since it possessed a more uniform force-deflection characteristic and was less likely to bind. Their conclusions were based on test data, not accident statistics. Conversely, it could be argued that the mesh column is less susceptible to binding since it functions by simple plastic deformation and does not depend on developing a friction force between concentric tubes.

In 1974, A.J. McLean analyzed North Carolina accident data for the calendar years 1971 and 1972 [50]. The file contained relatively numerous cases of mesh, ball and slotted columns. Table 6-5 shows that the drivers of mesh column cars had a 14 percent lower K+A injury rate in frontal crashes than the drivers of pre-Standard cars. The injury rates for ball and slotted columns were 27 and 25 percent lower, respectively. The report concluded that "the Saginaw ball-and-tube and the Ford slotted columns appear to provide a substantial protection to drivers involved in frontal impacts..... [whereas] the early Saginaw mesh column appears to have little to recommend it from an energy reduction viewpoint." It appears, however, that the observed injury rate differences for the alternative designs are not statistically significant (sample sizes are shown in Table 6-5). It is possible, then, that the report's conclusion goes beyond what can be inferred from the accident data.

A study by the New York State Department of Motor Vehicles, on the other hand, found a somewhat lower effectiveness for the Ford slotted column than the mesh column used by the other manufacturers [58]. The observed differences in effectiveness were apparently not statistically significant. Also, in this study, effectiveness was computed by comparing the injury rates to those for cars of the same manufacturer one year before full compliance. Since 1967 Fords incorporated a partial improvement of the steering assembly (padded hubs), the incremental benefit of full standard compliance would be less than for other manufacturers.

By far the most controversial studies, however, are those published in 1973 and 1974 by P.F. Gloyns et al. which compared the steering <u>wheel</u> and steering <u>column</u> energy absorbing devices [29], [30]. (See Sections 3.4.3 and 3.5 for background discussion.) Their studies are based on a non-probability sample of relatively severe frontal passenger car crashes in the area of Birmingham, United Kingdom. In the 1974 study, the sample consisted of 103 cars: 38 with the steering wheel EAD and 65 with the column EAD. The earlier study was based on a subsample

TABLE 6-5

NORTH CAROLNA INJURY RATES IN 1971-72 FOR UNRESTRAINED DRIVERS IN FRONT-TO-FRONT OR FRONT-TO-REAR COLLISIONS WITH A PASSENGER CAR

(McLean 1974)

Type of Column	N of Drivers	% K+A	Injury Reduction(%)
Pre-Standard (excluding 1967 Fords)	1862	10.0	-
Mesh	1459	8.6	14
Ball	1125	7.3	27
Slotted	987	7.5	25

of these crashes. In the 1974 study, the drivers of cars equipped with the wheel EAD had a significantly lower rate of serious chest injury than the drivers of column EAD cars. Table 6-6 shows that only 1 of the 38 drivers in the wheel EAD cars had AIS $\geq$ 3 chest injury, as opposed to 17 of the 65 column EAD car drivers [1]. The Chi-square statistic for Table 6-6 is 9.2, which indicates a statistically significant difference between the wheel and column EADs.

Gloyns' findings on chest injury must be tempered, however, by the results on overall injury. Table 6-7 shows that the drivers' overall AIS $\geq$ 3 injury rate is not significantly lower in the wheel EAD cars than in the column EAD cars (χ^2 = 1.9). But if the wheel EAD were indeed more effective in reducing chest injury and at least equally effective in preventing other injuries, a significant difference of overall injury rates would have been expected.

The study was based on a non-probability sample of accidents. Police provided initial accident notification and an investigation team selected appropriate accidents. Since the wheel EAD was less common than the column EAD in the United Kingdom, it is possible that somewhat more severe accidents involving the latter were selected, because there were more incidents to choose from. If so, this may have contributed to the higher injury rate for column EAD cars.

Gloyns et al concluded that "both these basic designs of steering system comply with FMVSS 203, although one has been shown to be ineffective in the field whilst the other one is apparently highly effective [30]." This seems to be a rather sweeping conclusion based on a fairly small non-probability sample of accidents and statistical findings that are not unequivocably significant.

TABLE 6-6

CHEST AIS $\geq$ 3 INJURY RATES FOR DRIVERS IN FRONTAL CRASHES, WHEEL EAD VS. COLUMN EAD, UNITED KINGDOM

(Gloyns & Mackay, 1974)

Cars with:	N of Drivers with:	
	Chest AIS < 3	Chest AIS $\geq$ 3
Steering wheel EAD	37	1
Column EAD	48	17

$\chi^2 = 9.2 \quad p < .01$

TABLE 6-7

OVERALL AIS $\geq$ 3 INJURY RATES FOR DRIVERS IN FRONTAL CRASHES, WHEEL EAD VS. COLUMN EAD, UNITED KINGDOM

(Gloyns & Mackay, 1974)

Cars with:	N of Drivers with:	
	Overall AIS < 3	Overall AIS $\geq$ 3
Steering wheel EAD	30	8
Column EAD	43	22

$\chi^2 = 1.9 \quad p > .10$

NHTSA sponsored a study, published in 1978, comparing wheel and column EAD performance in MDAI data collected in the United States [66]. The work was, perhaps, motivated by the controversy surrounding the British studies. There were not enough cases of steering wheel EAD vehicles on the MDAI file to produce statistically meaningful injury rates.

6.2.2 Comparative results from NCSS

The NCSS file contains a large probability sample of accident and injury cases involving each of the principal EAD types. The sample sizes range from 844 cases with the steering wheel EAD to 13,511 with the ball column. Nevertheless, no significant differences in effectiveness could be found among the EAD types.

Table 6-8 gives the fatal and hospitalizing steering assembly contact injury rate and the effectiveness (injury reduction when compared to pre-Standard) for each of the major EAD types. Table 6-9 further cross-classifies the injury rates by manufacturers and calculates effectiveness as the reduction of injury rate relative to pre-Standard vehicles of the same manufacturer. (GM and AMC are grouped together because both purchase their columns from the Saginaw Steering Gear Division of GM.)

Table 6-8 shows that the effectiveness of the 4 predominant column EAD types is quite similar: the mesh column (GM, AMC and Chrysler) reduced injury by 27 percent, the ball column (GM and AMC) by 36 percent and the slotted and grooved columns (Ford) by 39 percent each. Also, the column EAD in the foreign cars, which was usually of the mesh type, reduced injury by 38 percent. When they are added to the domestic mesh types, the average effectiveness for mesh is 32 percent.

TABLE 6-8

FATAL OR HOSPITALIZING STEERING ASSEMBLY CONTACT INJURY REDUCTION BY TYPE OF ENERGY ABSORBING DEVICE, NCSS

EAD Type	N of Cases	% with Fat/Hosp Steering Injury	Injury Reduction (%)
None (Pre-Standard excl. 1967 Fords)	3560	3.23	–
Mesh column	4542	2.36	27
Ball column	13,511	2.06	36
Slotted column	4311	1.97	39
Grooved column	3528	1.98	39
Slotted jacket & mandrel	1355	1.55	52
Wheel canister only	340	2.94	9
Wheel canister + column EAD	504	2.18	32
All wheel canister cases	844	2.49	23
Hub pad only (1967 Fords)	391	2.30	29
Post-Standard imported makes and models not listed in Table 3-12 (nearly all column EAD – mostly mesh)	3568	1.99	38

TABLE 6-9

FATAL OR HOSPITALIZING STEERING CONTACT INJURY REDUCTION
BY MANUFACTURER AND EAD TYPE, DOMESTIC VEHICLES,
NCSS

Manufacturer EAD Type	N of Cases	% with Fat/Hosp Steering Injury	Injury Reduction (%)
GM and AMC			
None	1824	3.02	-
Mesh column	2118	2.08	31
Ball column	13,511	2.06	32
FORD			
None (excl. 1967)	993	3.53	-
Hub pad only (1967)	391	2.30	35
Slotted column	4311	1.97	44
Grooved column	3528	1.98	44
CHRYSLER			
None	465	3.44	-
Mesh column	2197	2.55	26
Wheel canister	179	2.79	19
Slotted jacket & mandrel	1355	1.55	55

The slotted jacket and mandrel column EAD, used on Chrysler cars since 1974, had a slightly higher observed effectiveness (52%). The sample size for this type (1355), however, was substantially smaller than for the 4 preceding types and the difference in effectiveness is not statistically significant.

The NCSS file contains 844 cases of vehicles equipped with the steering wheel EAD (504 of which also have the mesh column). There were 21 drivers in these vehicles with fatal or hospitalizing steering assembly contact injury. NCSS is a much larger sample of steering wheel EAD cases than Gloyns' sample or the MDAI file. The observed effectiveness for steering wheel EAD vehicles was 23 percent and was lower than the observed effectiveness of any of the column EAD types. Moreover, in the subset of cars with steering wheel EAD alone, the effectiveness was just 9 percent. It was 32 percent in the cars with both the wheel and mesh column EAD.

When the effectiveness of the various EAD types was calculated separately by manufacturer (Table 6-9) the results were about the same as when the data were pooled (Table 6-8). Slightly higher effectiveness was observed among Fords, perhaps, because the pre-Standard injury rate, which was based on a relatively small sample, was fairly high.

A surprisingly high injury reduction (29 percent) was observed for the 1967 Fords, equipped with a hub pad only, relative to the other pre-Standard cars. In fact, the injury rate for 1967 Fords is based on just 391 NCSS cases and is not significantly different from the rate for other pre-Standard cars (see Table 6-11).

Even though the steering wheel EAD had the lowest observed effectiveness of all types, the difference of the steering assembly contact injury rates

TABLE 6-10

FATAL OR HOSPITALIZING STEERING ASSEMBLY INJURY RATES, WHEEL EAD VS. COLUMN EAD, NCSS

	N of drivers with	
	No Fat/Hosp. Steer. Inj.	Fat/Hosp. Steer Inj.
Steering wheel EAD	823	21
Column EAD	30,237	633

$\chi^2 = 0.78 \quad p > .10$

TABLE 6-11

FATAL OR HOSPITALIZING STEERING ASSEMBLY CONTACT INJURY RATES IN PRE-STANDARD CARS, PADDED HUB VS. NO PADDED HUB, NCSS

	N of drivers with	
	No Fat/Hosp. Steer. Inj.	Fat/Hosp. Steer. Inj.
Padded hub ('67 Fords)	382	9
No padded hub (all other pre-Standard)	3445	115

$\chi^2 = 1.0 \quad p > .10$

for wheel and column EAD is not statistically significant (see Table 6-10). So it cannot be concluded from NCSS that the wheel EAD is less effective than the column EAD.

On the other hand, the NCSS data clearly show that the column EAD is not "ineffective in the field" as Gloyns and Mackay concluded. The NCSS sample is large enough to statistically invalidate Gloyns' contention that the wheel EAD is "highly effective" relative to the column EAD (although "highly effective" would have to be defined before a specific test could be performed).

Moreover, subsequent analyses in this chapter will show that the steering wheel EAD produced about the same injury pattern as the column EAD (Section 6.3.2) and did not compress more readily than the column EAD under heavy load (Section 6.5.2). These results are also at variance with Gloyns' explanation of why the steering wheel EAD is more effective.

6.3 Injury reduction by body region

The distribution of steering assembly contact injuries, by body region, was discussed in Section 3.3.1. Table 3-9 showed that the chest was the predominant location: 41 percent of the fatal or hospitalizing steering assembly contact injuries and 52 percent of the more serious injuries among them, with AIS 3-6, were in the chest region. The head area (including the neck and face) was the next most frequent location, but the majority of these injuries were not serious. The abdomen ranked second in serious injuries. The arms and legs were the least common injury location.

Section 3.3.2 described the mechanisms whereby pre-Standard steering assemblies were causing injuries to the various body regions. Section 3.5 explained how the equipment installed in response to Standards 203 and 204 might alleviate specific types of injury. In particular:

- Chest injuries might be reduced by the energy absorbing device, intrusion prevention and the improved steering wheel (padding, broader hub and spokes).

- Abdominal injuries might be reduced by the energy absorbing device, the improved steering wheel, intrusion prevention, and reduction of the steering wheel's diameter.

- Head and neck injuries might be reduced by the improved steering wheel, removal of horn rings, reduction of the steering wheel diameter, intrusion prevention, and a more horizontal steering angle.

- Arm injuries might be reduced by the improved steering wheel and removal of horn rings.

- Leg injuries might be reduced by the relatively soft jacket surrounding the steering shaft and a more horizontal steering angle.

To what extent does the accident experience with post-Standard steering assemblies support the conjectures about injury reduction?

6.3.1 Results from earlier studies

In 1969, D.F. Huelke reported that the post-Standard steering assemblies were reducing thorax and abdominal injuries substantially, but that drivers continued to risk nondangerous facial injury from contacting the steering wheel rim [33]. His conclusion was based on a review of in-depth accident investigations, not a statistical study. The injury reduction was attributed to the prevention of intrusion and the successful compression of the column by the driver. Also in 1969, L.M. Patrick published a review of in-depth investigations and crash tests with post-Standard steering assemblies [65]. He noted that the design of the steering wheel played an important role in injury causation. The improved wheels with thicker spokes which were introduced at about the same time as the Standards, especially the ones with 3 spokes, reduced injuries to all body regions by preventing concentrated loads. Patrick concluded that the wheel improvements should be made universal because some cars still had unimproved wheels which were failing in crashes (see Figures 3-35 - 3-37).

In the same year, Lundstrom & Cichowski published their statistical analysis of ACIR data, which included an examination of injury rates by body region [45]. They found that Standards 203 and 204 were associated with virtually identical reductions in torso injury (32 percent) and head injury (27 percent) due to steering assembly contact. Both reductions were statistically significant (see Table 5-1).

In 1970, Nahum, Siegel and Brooks published a statistical analysis of MDAI data collected in the Los Angeles area [56]. (Their sample is described in Section 5.1.1.) Table 6-12 shows that there was no statistically significant difference between the distribution, by body region, of the pre-Standard and post-Standard steering assembly contact injuries (of any severity). In other words, the Standards were not significantly more effective against one type of injury than against the others. Table 6-12 does show, however, that abdominal injuries had the largest relative decrease as a result of the Standards while arm and leg injuries had the largest relative increase - i.e., the highest observed effectiveness was against abdominal lesions; the lowest was against injuries to the limbs. The high incidence of head/neck lesions is due to the inclusion of minor injuries in the tabulation.

TABLE 6-12

BODY REGIONS OF NONFATAL LESIONS* DUE TO STEERING ASSEMBLY, PRE VS. POST-STANDARD, UCLA IN-DEPTH ACCIDENT INVESTIGATION (Nahum, Siegel & Brooks, 1970)

	Pre-Standard Injuries		Post-Standard Injuries	
Body Region	N	Col. %	N	Col. %
Chest	48	33	46	30
Head/neck	59	40	66	43
Abdomen	20	13	10	6
Arms/legs	21	14	33	21

$\chi^2 = 6.24$ df = 3 $p > .10$

*Including minor injuries

6.3.2 NCSS Results

The results from NCSS indicate that Standards 203 and 204 are effective in reducing injury to all major body regions and that there are no substantial differences in effectiveness between body regions. Table 6-13 shows that the drivers of post-Standard cars had a 28 percent reduction of fatal or hospitalizing chest injury due to steering assembly contact. Thus, the chest injury reduction differs just slightly from the overall effectiveness of 38 percent, found in Chapter 5. The reduction of injury to the head and neck was observed to be slightly higher (45 percent) and so, too, for the arms and legs (42 percent). The observed effectiveness for abdominal and pelvic injury was slightly lower than average (22 percent).

Table 6-14 shows, however, that there was no statistically significant difference between pre- and post-Standard cars in the distribution of injuries by body region. In other words, the observed differences in effectiveness for the various body regions are also nonsignificant.

TABLE 6-13

FATAL OR HOSPITALIZING STEERING CONTACT
INJURY REDUCTION BY BODY REGION, NCSS

Body Region	% with Fat/Hosp Steering Injury Pre-Standard	Post-Standard	Reduction for Post-Standard
Chest/shoulder	1.19	0.86	28%
Head/neck	0.96	0.52	45%
Abdomen/pelvis	0.53	0.41	22%
Arms/legs	0.46	0.27	42%
N of drivers	3951	31,659	

TABLE 6-14

BODY REGIONS OF FATAL OR HOSPITALIZING
STEERING ASSEMBLY CONTACT INJURIES,
PRE-VS. POST-STANDARD, NCSS

	Pre-Standard Injuries		Post-Standard Injuries	
Body Region	N	Col. %	N	Col. %
Chest/shoulder	47	38	273	42
Head/neck	38	31	166	25
Abdomen/pelvis	21	17	131	20
Arms/legs	18	14	84	13

$\chi^2 = 2.21$ df = 3 $p > .10$

What are the implications of this approximate equality of effectiveness by body region? The following conjectures should be considered:

(1) The reduction of arm and head injury can probably not be attributed to the successful compression of the column by the driver: the mass of the head or arm is too small to produce column compression when they contact the wheel. The injury reduction then, although partially due to the prevention of intrusion, must be attributed to a large extent to the removal of horn rings and metal trim on the steering wheel, the padding of the hub, the reduced diameter of the steering wheel, and the use of stronger but somewhat flexible materials in the spokes and rim. These improvements, which were not strictly required for compliance with the Standards, appear to have contributed substantially to their effectiveness.

(2) Since serious chest and abdominal injuries usually involve substantial driver loads on the steering wheel - more than could be absorbed by padding - their substantial reduction by the Standards must be due, in large measure, to the successful compression of the column by the occupant in many crashes.

In other words, if the manufacturers had designed and installed a foolproof energy absorbing device while neglecting to make any steering wheel improvements not strictly required by the Standards, injury reduction for the chest and abdomen would have been significantly higher than for the head and arm. On the other hand, if the energy absorbing devices' performance in the field were highly unsatisfactory, injury reduction for the chest and abdomen would have been significantly lower. Since, in fact, it was neither higher nor lower, the most plausible conjecture is that the improved steering wheel and the energy absorbing devices have both provided substantial benefits, even though the latter is not foolproof (see Section 6.5).

"Fatal or hospitalizing" steering contact injuries cover a spectrum of severity, ranging from non-dangerous injuries with largely precautionary hospitalization to, of course, fatalities. Table 6-15 shows that the Standards are nearly equally effective across the severity spectrum. They reduced AIS $\geq$ 2 injuries requiring hospitalization by 34 percent, AIS $\geq$ 3 injuries by 26 percent and AIS $\geq$4 by 34 percent.

In Section 6.2.2 it was shown that drivers of cars with the steering wheel EAD did not have a significantly lower overall steering contact injury rate than the drivers of column EAD cars. The observed rate, in fact, was somewhat higher. Table 6-16 shows that, furthermore, drivers of the two types of cars had nearly identical injury distributions, by body region. There also was no significant difference in the severity of their injuries. There is no evidence in NCSS to corroborate Gloyns' claim that the steering wheel EAD is especially effective in preventing chest injury [29].

Appendix C contains a listing of all fatal or hospitalizing steering assembly contact injuries on the NCSS file, including case numbers and pertinent vehicle and occupant information.

6.4 Side effects of Standards 203 and 204

Because of the compressible devices installed in response to Standards 203 and 204, the steering wheel no longer moves rearward relative to the windshield and instrument panel, but, on the contrary, can be compressed forward by the driver during a crash. (See, for example, Figure 3-28 or 3-30.) There were questions whether the post-Standard steering wheel might allow the driver's body to move forward to the point where his head or legs contact the windshield or instrument panel with resultant injuries.

TABLE 6-15

FATAL OR HOSPITALIZING STEERING CONTACT INJURY REDUCTION BY SEVERITY LEVEL, NCSS

Fat/Hosp Steering Injury with:	Injury Rate (%) Pre-Standard	Post-Standard	Reduction for Post-Standard
AIS ≥ 2	2.43	1.60	34%
AIS ≥ 3	1.57	1.16	26%
AIS ≥ 4	0.76	0.50	34%
N of drivers	3951	31,659	

TABLE 6-16

FATAL OR HOSPITALIZING STEERING ASSEMBLY CONTACT INJURY PATTERNS FOR WHEEL EAD VS. COLUMN EAD, NCSS

(a) By Injury Severity*

	AIS 1 - 2	AIS 3 - 6
Steering wheel EAD	11	10
Column EAD	252	357

$\chi^2 = 1.01 \quad p > .10$

(b) By Body Region **

	Head, Face, Neck Arms, Legs	Chest, Abdomen, Shoulder
Steering wheel EAD	8	13
Column EAD	242	391

$\chi^2 = 0.0002 \quad p > .10$

* Cases with AIS=8 excluded

** Categories were reduced from 4 to 2 to assure "expected" cell entries greater than 5

D.F. Huelke, in his 1969 review of in-depth accident investigations, noted that drivers of post-Standard cars risk breaking facial bones by contacting the instrument panel after the steering column is compressed [33]. L.M. Patrick also reviewed in-depth cases in 1969 and concluded that "driver knee impacts are more prevalent with the collapsible columns and injuries occur when the impact is near the rigid section of the instrument panel adjacent to the steering column [65]."

Neither study, however, was based on statistical analysis of a large accident data file.

The NCSS data, on the other hand, do not suggest that injuries due to other components increased as a consequence of steering column compression or nonintrusion. This conclusion is based on an analysis of NCSS drivers in frontal crashes who did contact the steering assemblies of pre or post-Standard 203 and 204 cars. What other components on the front interior surface of the passenger compartment did they contact? Were there any differences between pre- and post-Standard cars in the likelihood of contacting the other components? How severe were the resultant injuries? (The final NCSS file - which became available in November 1980 - was used for this analysis because it contains records of up to 6 contact points and injuries per person.)

The lowest section of Table 6-17 shows that there were no significant differences between the pre- and post-Standard cars in this regard. In the pre-Standard cars, there were 358 drivers who contacted the steering assembly and another component of the front interior surface of the passenger compartment (the instrument panel, the windshield, the rear-view mirror, etc.). Since there were 3983 pre-Standard car drivers, this is a contact frequency of 8.99 percent. In the 31,989

TABLE 6-17

OTHER OBJECTS CONTACTED BY DRIVERS WHO CONTACTED THE STEERING ASSEMBLY, PRE- VS. POST-STANDARD 203 AND 204, NCSS

Other Object Contacted	Pre-Standard	Post-Standard
Instrument Panel		
N of drivers with steering contact	225	1634
% of all drivers**	5.65	5.11
Change for post-Standard		-10% *
Windshield		
N of drivers with steering contact	116	1094
% of all drivers	2.91	3.42
Change for post-Standard		+17%*
Other frontal interior object***		
N of drivers with steering contact	133	1257
% of all drivers	3.34	3.93
Change for post-Standard		+18%*
Any of the above		
N of drivers with steering contact	358	2810
% of all drivers	8.99	8.78
Change for post-Standard		-2 %****

* Not statistically significant (α = .01)

** There are 3983 pre-Standard and 31,989 post-Standard drivers

*** NCSS contact codes 4-14 or 90

**** Not statistically significant (α = .05) post-Standard cars, there were 2810 drivers who contacted the steering assembly and another frontal component: a contact frequency of 8.78 percent. Thus, there was a nonsignificant 2 percent decrease in the likelihood of contacting the steering wheel and another frontal component. In other words, the NCSS data do not suggest that the successful compression/nonintrusion of the steering column has led to increased contact with other objects.

Table 6-17 also subdivides the other contacts by component. The drivers of post-Standard cars were somewhat less likely to contact the instrument panel plus steering assembly than the pre-Standard car drivers, but more likely to contact the windshield or other frontal components. The differences were not significant, however, at the .01 level (which was used to avoid spurious significant results when multiple tests are performed.)

Moreover, Table 6-18 shows that there were no significant differences in fatal or hospitalizing injuries due to other components, for pre- vs. post-Standard car drivers who contacted the steering assembly. In the pre-Standard cars, there were 57 drivers who contacted the steering assembly (not necessarily injury-producing) and sustained fatal or hospitalizing injury from another component of the frontal interior surface of the passenger compartment. Since there were 3983 pre-Standard cars, this is an injury rate of 1.43 percent. The corresponding injury rate in the post-Standard cars was 1.30 percent. Thus, there was a nonsignificant 9 percent decrease in the likelihood of contacting the steering wheel and sustaining serious injury from another frontal component. The NCSS data suggest that Standards 203 and 204 did not have negative side effects of increased injury from other components as a result of steering column compression/nonintrusion.

TABLE 6-18

FATAL OR HOSPITALIZING INJURIES FROM NON-STEERING CONTACT POINTS, FOR DRIVERS WHO ALSO CONTACTED STEERING ASSEMBLY, PRE- VS. POST-STANDARD 203 AND 204, NCSS

Other Object Contacted with Fat/Hosp Injury	Pre-Standard	Post-Standard
Instrument Panel		
N of drivers with steering contact	25	159
% of all drivers**	0.63	0.50
Change for post-Standard		-21%*
Windshield		
N of drivers with steering contact	16	157
% of all drivers	0.40	0.49
Change for post-Standard		+22%*
Other frontal interior object***		
N of drivers with steering contact	19	131
% of all drivers	0.48	0.41
Change for post-Standard		-14%*
Any of the above		
N of drivers with steering contact	57	416
% of all drivers	1.43	1.30
Change for post-Standard		-9%****

* Not statistically significant ($\alpha = .01$)

** There are 3983 pre-Standard and 31,989 post-Standard drivers

*** NCSS contact codes 4-14 or 90

**** Not statistically significant ($\alpha = .05$)

Table 6-18 shows that the differences between pre- and post-Standard cars on a component by component basis were also nonsignificant (α = .01). The observed results for serious injuries, however, parallel the results for all types of contact (Table 6-17): an increase in the windshield contact injury rate, but a decrease for the instrument panel.

The differences of injury rates in Table 6-17 and 6-18 were tested by calculating the Chi-square statistic for the 2x2 table of Standard 203 compliance by contact, using weighted NCSS cell frequencies. Since these inflated statistics were all "nonsignificant," they would have remained so after proper adjustment to account for the NCSS sampling plan.

The NCSS results - no major negative side effects for Standard 203 and 204 - are consistent with engineering intuition. In the vast majority of cases, even the pre-Standard steering column does not intrude at all or intrudes only very little (see Table 6-1). The post-Standard steering column usually does not compress more than a few inches (see Table 6-20). Thus, in only a relatively small percentage of cases is the intrusion reduction or compression of sufficient magnitude to significantly increase the risk of contact with other components. Even in these cases, the "ridedown" provided by the compressing column, by reducing the driver's velocity relative to the passenger compartment, may sometimes reduce the severity of injury from the other components.

The NCSS analyses of this section must be viewed with a little extra caution. Contact and injury rates (for non-steering components) were calculated for drivers who contacted the steering assembly - according to NCSS. But contact information is often missing in NCSS in cases of minor injury. Noninjury contacts are not recorded at all. The drivers who contacted the steering wheel without injury would be missing from the analyses here.

6.5 Compressibility of the energy-absorbing devices

The steering wheel and column energy absorbing devices installed in response to Standard 203 were designed to compress or telescope when the driver contacted the steering wheel (see Sections 3.4 and 3.5). They were to compress at a controlled rate, absorbing the load of the driver's torso at a nondangerous force-deflection level.

When Standard 203 steering assemblies had been introduced in the 1967 model year by GM, AMC and Chrysler, highway accident experience soon revealed that the EAD, when it compressed properly, was highly effective in reducing injury severity (see Figures 3-26 - 3-32). Before long, however, accident investigations showed that the EAD did not always compress properly (Figures 3-33 and 3-34).

The tendency of the EAD to bind rather than telescope has been the most controversial question surrounding Standard 203. (See the background discussion in Section 3.5.) It is beyond the scope of this report to answer it definitively, of course. But an evaluation of Standard 203 must sketch out what are the critical issues in the controversy and attempt to provide a quantitative assessment.

The issues that have been raised are, primarily, the following:

- Is there really a problem of the EAD failing to compress or is it just a statistical figment? How severe is the problem?
- What causes binding of the EAD? Is it due to nonaxial crash forces? Off-center occupant loading? Vehicle damage? Vertical column intrusion?
- How do the various EAD types compare in regard to compressibility?

- How does the problem of binding relate to the compliance test for Standard 203?
- What is the best way to measure compression due to occupant loading? To what extent is EAD compression the result of vehicle damage rather than occupant loading?
- What is the appropriate force-deflection characteristic for the EAD?

The issues will be examined on the basis of existing accident studies and an analysis of the MDAI file. The NCSS data could not be used here because they do not contain information on column compression.

6.5.1 Results and conclusions of earlier studies

The compliance test for Standard 203 requires that the force in the column must not exceed 2500 pounds during contact with a body block (see Section 3.4.2). In fact, the energy absorbing columns installed in response to Standard 203 had a maximum force deflection characteristic of 1800 pounds [65]. An 80 pound body block moving at 15 mph has a kinetic energy of about 600 foot-pounds. If the EAD were to absorb all of this energy, it would have to compress 4 inches, or more, if the force deflection characteristic is limited to 1800 pounds maximum. At first glance, then, frontal crashes with Delta V of 15 mph or more (or head-on crashes with relative velocities of about 30 mph or more) should result in substantial (4-inch) column compression.

Lundstrom and Cichowski's 1969 study of Motors Insurance Corporation data showed that column compression in highway crashes was usually much less [45]. Their study was based on 222 cases of 1968 GM cars in frontal crashes with column compression, steering wheel deformation or driver injury. Table 6-19 shows that the average compression in crashes with relative velocity 26-35 mph (i.e., Delta V approximately 15 mph) was just 1.4 inches.

TABLE 6-19

AVERAGE COLUMN COMPRESSION BY RELATIVE VELOCITY,
FRONTAL CRASHES WITH COLUMN COMPRESSION,
STEERING WHEEL DEFORMATION OR DRIVER INJURY,
1968 GM CARS, MIC DATA
(Lundstrom & Cichowski, 1969; N = 222)

Relative Crash Velocity (mph)	Average Column Compression (inches)
0-15	0.4
16-25	0.8
26-35	1.4
36-45	2.8
46-55	3.5
56+	4.5

L.M. Patrick also observed, in 1969, that column compression in highway accidents was considerably less than in laboratory bench tests [65]. But the drivers in these highway accidents usually did not suffer serious injuries. Patrick concluded that the columns did not compress because they were not loaded heavily enough to cause compression (for, if they had failed to compress under heavy load, the drivers could have been seriously injured). The driver load on the column is often lighter than what would have been expected from the Delta V because:

- a large portion of the torso's kinetic energy can be dissipated through leg contact with the instrument panel, bracing during impact, seat belts and other contacts.

. the torso's kinetic energy is also partly dissipated during the vehicle's "ride-down" phase of the collision -- i.e., the gradual plastic deformation and deceleration of the vehicle that takes place during collision contact while the driver is stationary relative to the vehicle.

Nevertheless, Patrick also concluded that "columns do not collapse in some impacts when the force is obviously above the collapse force as evidenced by gross deformation of the stiff steering wheel." In other words, low column compression at relatively high Delta V should not be considered a sign of column failure unless it is accompanied by severe deformation of the wheel.

He found that "the column collapse is only minimal in right-front impacts."

Finally, Patrick concluded that the 1800 pound force deflection characteristic used in post-Standard columns is appropriate because "an 1800-pound force distributed over the thorax with a stiff steering wheel will not produce serious thoracic injuries." He added a proviso that "the wheels should be designed so they will not deform in a manner which will result in concentrated loads being applied." In other words, the improved steering wheels that manufacturers installed at about the same time that Standard 203 was promulgated (see Section 3.4.3) enhanced the effectiveness of the EAD.

The energy absorbing columns (except the Ford mini-column) are designed to collapse under 2 kinds of loads: from underneath, due to vehicle deformation and from the top, due to driver load. The shear capsule is generally designed to separate only under occupant load. D.F. Huelke concluded, on the basis of in-depth investigations, that the amount of compression due to vehicle deformation exceeds, on the average, the amount due to driver load [33]. By implication, shear capsule separation provides a better measure of driver energy absorption.

Gloyns et al. had a number of observations about EAD compressibility in their 1973 and 1974 papers comparing the steering wheel and column EAD [29], [30]. Their main conclusion was that the steering wheel EAD successfully compresses under occupant loading while the column EAD often binds and fails to compress under driver load. They attribute the binding of the column to nonaxial load, which occurs for several reasons. The most common reason is described in the following sequence of events:

"Frontal damage to the vehicle begins and the bottom of the column, adjacent to the toepan, undergoes some deformation which is non-axial with respect to the column. When the driver contacts the wheel, the telescoping sections in the column are already locked. A large load is developed between the steering wheel and the driver's chest which, in turn, causes further bending and locking. As the loads rise the steering wheel begins to deform giving rise to load concentration, thus effectively lowering the load which can be tolerated by the chest without injury [30].

Since Gloyns felt that initial vehicle damage is the primary cause of column binding and since the compliance test for Standard 203 is a bench test of an undamaged steering assembly, he concluded that the test was unrealistic and that it allowed the manufacturers to install an ineffective device.

Gloyns also pointed out that the more or less horizontal driver kinetics in a crash are usually nonaxial with respect to the column (which is not horizontal – especially not in the small English Fords of Gloyns' sample) and this further increases the likelihood of binding.

He claimed that shear capsule separation is not necessarily a good measure of column compression by the driver since, just like EAD compression, capsule separation can be a consequence of vehicle damage.

Finally, he concluded that the steering wheel EAD is more effective than the column EAD because it is far less vulnerable to failure under nonaxial impact. This is because the steering wheel EAD aligns itself to the plane of the driver's torso. (See Figure 3-21 and discussion in Sections 3.4.3 and 3.5.) Moreover, when the steering wheel aligns itself to the driver's chest, the load is spread over a large area - thus effectively increasing the permissible force-deflection characteristic of the steering wheel EAD.

In 1975, Garrett and Hendricks performed a detailed review of steering column performance in a rather large sample of Calspan Corporation MDAI cases as well as crash and bench tests [28]. Their findings largely support Gloyns' conclusions: there are many instances of column binding and the primary cause of binding is <u>nonaxial</u> force. They corroborated both of the sources of nonaxial force described by Gloyns (vehicle damage; nonhorizontal column alignment) and found two additional sources:

- upward intrusion or rotation of the column
- oblique crash forces

Thus, in all, Garrett and Hendricks described 4 causes of nonaxial load. Here is what they had to say about each of them:

They reviewed many accident cases in depth to illustrate the effect of vehicle damage on column performance. The effect depends on the precise location of the damage (horizontal and vertical) and the design and location of the steering assembly. There are too many factors to permit a prediction of column performance, although some general trends can be observed.

The angle of driver motion relative to the column alignment is an extremely important determinant of column performance: the smaller the angle, the better the performance. The bench tests reported by Du Waldt, in which vehicle damage was obviously not a factor, isolated the effect of column angle [15]. A column that performed well in a Standard 203 compliance test showed little compression when struck by the body block at a 25-30 degree angle. Moreover, the alignment of the steering wheel spokes had a significant effect on compression. Since spoke alignment during a crash is a more or less random variable, it is difficult to predict column performance. (Figure 3-36 shows the consequence of unfavorable spoke alignment and binding.)

Vertical intrusion and rotation of the column affects binding by changing the angle of driver motion relative to the column or, perhaps, locking up the telescoping devices prior to driver contact. When the intrusion and rotation is upward, the angle increases and the column binds (see Figure 3-33). When the rotation is downward, the angle decreases and compression may be enhanced (see Figures 3-30 and 3-31).

Oblique crash forces result in driver kinetics that are lateral with respect to the column alignment. They may also, at times, result in lateral rotation of the column. The net result is an angle between driver movement and column alignment, which reduces column compression (see Figure 3-34). Du Waldt's bench tests, however, showed that forces just 15 degrees from frontal did not reduce column compression. A fairly large lateral component is apparently required.

Finally, Garrett and Hendricks presented aggregate statistics on column EAD compression in the Calspan MDAI cases: 76 percent of the columns studied compressed 1 inch or less. They cited T.E. Anderson's 1974 study [5], also performed at Calspan, which claimed that energy absorbing columns were not reducing injuries. They concluded, essentially, that Standard 203 was not working in the field because of the nonaxial forces that exist in highway accidents but not in the compliance test.

It must be noted, however, that their aggregate statistic (76 percent of the columns compressing 1 inch or less) is inappropriate because it includes crashes of low severity and crashes where the driver never contacted the steering wheel - L.M. Patrick's comments about cases with low compression need to be recalled here. Anderson's study appears to contain serious biases and is inconsistent with other effectiveness results (see Section 5.1.3). It seems, then, that Garrett and Hendricks have been too pessimistic in their conclusions.

Nonaxial loads or vehicle damage can cause locking up of telescoping column components other than the EAD - e.g., the steering shaft or the shift tube - and result in column noncompression.

6.5.2 Results from the MDAI file

The Multidisciplinary Accident Investigation (MDAI) data file contains slightly over 2000 cases of frontal impacts in which the driver contacted the steering wheel or spokes (as of June 1980). These are the types of crashes in which the driver is most likely to compress the energy-absorbing device. The MDAI file is not a probability sample of accidents and is considered unreliable for calculating injury rates, but it is the most extensive and accurate source of information on EAD compression in highway accidents. "Frontal" crashes are defined here to be those in which the 1st letter of the CDC is F and the 4th letter is W or N - i.e., those in which there was significant structural engagement at the front of the car [11].

Table 6-20 shows the distribution of EAD compression and shear capsule separation (where applicable) by EAD type. The designs which experienced the most compression were the slotted jacket and mandrel (Chrysler), the mesh column (GM, AMC, Chrysler) and the ball column (GM, AMC). For these 3 types, the percentage of cars with at least 1 inch of column compression was 51, 40 and 36 and the percentage with at least 1 inch of shear capsule separation was 37, 33 and 30, respectively.

The Ford slotted column experienced less compression: 28 percent of the cases had 1 inch or more of EAD compression and 20 percent had at least 1 inch of shear capsule separation. Since the slotted column design is fairly similar to the mesh column and since the slotted column performed very well in reducing injury (see Table 6-8), it is surprising that it should display less compression than the mesh type. A possible explanation is that the Ford steering wheels and spokes may be designed to absorb more energy than other manufacturers' wheels. The more energy is dissipated in the wheel, the less would be absorbed by column compression.

The Ford grooved column and the steering wheel EAD experienced at least 1 inch of compression in 22 and 21 percent of the cases, respectively. Their rate of compression is lower than the other EAD types, in part, because they do not

TABLE 6-20

ENERGY ABSORBING DEVICE COMPRESSION AND SHEAR CAPSULE SEPARATION, BY EAD TYPE, FRONTAL CRASHES* IN WHICH DRIVERS CONTACTED WHEELS OR SPOKES, MDAI

EAD Type Compression Type	% of Cases with Inches of Compression: 0	 0.1-0.9	 1.0-2.9	 3.0+	 N of Cases
Mesh column					
EAD compression	34	26	18	22	525
Shear capsule separation	38	29	23	10	502
Ball column					
EAD compression	41	23	18	18	1053
Shear capsule separation	40	30	18	12	1048
Slotted column					
EAD compression	53	19	19	9	548
Shear capsule separation	52	28	14	6	508
Grooved column					
EAD compression	63	15	16	6	200
Slotted jacket & mandrel					
EAD compression	29	20	34	17	71
Shear capsule separation	48	15	32	5	59
Steering wheel EAD					
Maximum compression	50	29	13	8	38

* 1st letter of CDC is F and 4th letter is W or N

collapse as a result of vehicle damage, but only under driver load. Nevertheless, the low rate of compression for the grooved column is surprising in view of the high level of injury reduction observed for that device (see Table 6-8). There are 2 possible reasons for the reduced compression observed in the MDAI file: (1) The Ford steering wheels and spokes may have absorbed relatively more energy. (2) The grooved column design allows for partial restitution after it has been compressed in a crash. This feature may have been unknown to many MDAI teams. Since they measured column compression at rest, they underestimated the maximum compression under load [60].

The relatively lower compression of the steering wheel EAD in the MDAI data is consistent with its lower effectiveness in NCSS (see Table 6-8). Both statistics, however, are based on smaller samples than were obtained for any of the other devices.

Table 6-20 includes frontal crashes of low severity. They have been excluded in Table 6-21, which includes only the frontal crashes with CDC extent zone 3 or greater. The majority of the cars - 53 percent - had at least 1 inch of column compression in these crashes. Close to half of the cars - 45 percent - had at least an inch of shear capsule separation (or EAD compression in cars not equipped with shear capsules). The best performers were, again, the slotted jacket and mandrel, the mesh column and the ball column.

There is an evident disparity between shear capsule separation and EAD compression in the more severe impacts. For example, in Table 6-21, 40 percent of the mesh columns had 3 inches or more EAD compression but only 20 percent had 3

TABLE 6-21

ENERGY ABSORBING DEVICE COMPRESSION AND SHEAR CAPSULE SEPARATION, BY EAD TYPE, IN SEVERE FRONTAL* CRASHES WHERE DRIVER CONTACTED WHEELS OR SPOKES, MDAI

EAD Type Compression Type	% of Cases with Inches of Compression: 0	0.1-0.9	1.0-2.9	3.0+	N of cases
Mesh column					
EAD compression	14	20	26	40	240
Shear capsule separation	19	25	36	20	222
Ball column					
EAD compression	20	24	23	33	443
Shear capsule separation	22	29	27	22	448
Slotted column					
EAD compression	33	22	30	15	250
Shear capsule separation	32	36	23	9	225
Grooved column					
EAD compression	55	17	19	9	96
Slotted jacket & mandrel					
EAD compression	12	21	40	27	33
Shear capsule separation	34	12	42	12	26
Steering wheel EAD					
Maximum compression	22	39	22	17	18
ALL TYPES					
EAD compression	25	22	25	28	1080
Shear caps. sep. if equipped - otherwise otherwise EAD comp.	27	28	28	17	1035

*1st letter of CDC is F, 4th letter is W or N, extent zone is 3-9.

inches or more shear capsule separation. Comparable disparities were observed for the other designs. Whenever substantial EAD compression is not matched by shear capsule separation, it means that the collapse resulted from vehicle deformation, not driver loading. Since EAD collapse was observed, in Table 6-21, to exceed capsule separation, it can be concluded that the former is not a good measure of compression by driver load (except in the grooved column and the steering wheel EAD).

Table 6-22 compares EAD collapse and capsule separation from another point of view. The upper half of Table 6-22 shows their distribution in frontal crashes (of all severities) in which the drivers contacted the steering wheel or spokes. It shows that 16 percent of the cars had 3 inches or more of EAD collapse but only 10 percent had 3 inches or more of capsule separation - i.e., the former measurement exaggerates compression due to driver load.

The lower half of Table 6-22 shows the distribution of the collapse measurements in frontal crashes where the driver did <u>not</u> contact the steering wheel or spokes. Collapse in these types of crashes would be due to vehicle deformation, not driver load. It shows that only 1 percent of these cars had 1 inch or more of shear capsule separation and none had 3 inches or more. By contrast, 3 percent of the cars had 1 inch or more of EAD compression. This part of Table 6-22 suggests that shear capsule separation due to causes other than driver loading is not very common.

Table 6-21, although limited to crashes with damage extent zone 3 or greater, still contains cases in which driver contact with the steering assembly is of minimal severity. As such, it still understates the tendency of the EAD to compress under heavy driver load. Table 6-23 presents a fairer picture of EAD performance under heavy load. It is limited to those cases in which

TABLE 6-22

EAD COMPRESSION VERSUS SHEAR CAPSULE SEPARATION
FRONTAL CRASHES* OF CARS WITH SHEAR CAPSULES, MDAI

(a) Driver Contacted Wheel or Spokes

% of Cars with	EAD Compression	Shear Capsule Separation
0 inches	42	42
0.1 - 0.9	23	29
1.0 - 2.9	19	10
3.0+	16	10
N of cars	2197	2117

(b) Driver Did Not Contact Wheel or Spokes

% of Cars with	EAD Compression	Shear Capsule Separation
0 inches	91	96
0.1 - 0.9	6	3
1.0 - 2.9	2	1
3.0+	1	0
N of cars	676	678

* 1st letter of CDC is F and 4th letter is W or N.

- The shear capsule separated at least 3 inches (or the EAD compressed this amount in cars not equipped with shear capsules) – these are cases in which there was successful compression under substantial driver load.

- The steering wheel or spokes were severely deformed or broken, but there was less than 1 inch of shear capsule separation (or EAD compression in non-shear capsule cars) – these are cases in which the column failed to compress despite the presence of a substantial driver load.

Table 6-23 shows that there were 223 cases of "successful" compression and 247 "failures" to compress under heavy driver load. In other words, given the somewhat arbitrary criteria for "success" and "failure" used here, the failures outnumber the successes, but by a small margin.

Table 6-23 seems the fairest way to evaluate EAD compressibility. If there was no severe wheel deformation and no substantial EAD compression, then the driver load was probably dissipated by means other than the steering assembly, as L.M. Patrick suggested (see Section 6.5.1). This type of case, then, could not fairly be called a "failure" of the column to compress. It has, therefore, been excluded from Table 6-23.

The implications of Table 6-23 are twofold:

(1) Failure of the column to compress under heavy driver load is indeed a serious problem.

(2) It is not as serious as suggested by gross aggregate statistics such as Table 6-20 or Garrett and Hendicks' results. Close to half of the columns did successfully compress under driver load.

TABLE 6-23

SUCCESSES* AND FAILURES** OF EAD COMPRESSION UNDER HEAVY LOAD, BY EAD TYPE, FRONTAL*** CRASHES WHERE DRIVER CONTACTED WHEEL OR SPOKES, MDAI

EAD Type	N of Successes	N of Failures
Mesh column	50	51
Ball column	125	96
Slotted column	30	66
Grooved column	12	25
Slotted jacket & mandrel	3	4
Steering wheel EAD	3	5
ALL TYPES	223	247
	(47%)	(53%)

* At least 3 inches shear capsule separation (or EAD compression if not equipped with shear capsule)

** Steering wheel or spokes severely deformed or broken - less than 1 inch shear capsule separation (or EAD compression if no shear capsule)

*** 1st letter of CDC is F and 4th letter is W or N

Table 6-23 shows that the ball column was the only EAD type on the MDAI file with more "successes" than "failures." The slotted and grooved columns were the only types with significantly more "failures" than "successes." This may again be a reflection on the Ford steering wheel and spokes, which were specifically designed to absorb substantial energy by deforming. There is nothing in the injury data (Table 6-8) to suggest that the Ford columns are less effective than the other designs.

Table 6-24 shows the effect of nonaxial PDOF on EAD performance. In 1342 cases with 12:00 PDOF (forces within 15 degrees of axial), 12 percent of the cases had at least 3 inches of shear capsule separation and 32 percent had at least 1 inch. In the 892 cases with 11:00 or 1:00 PDOF (forces 15-45 degrees away from axial), only 6 percent had at least 3 inches separation and 24 percent had at least 1 inch.

The reduced compression at nonaxial PDOF is only in part due to inferior column performance. The principal reason for less compression is that the driver is less likely to heavily load the column, since more of his kinetic energy is dissipated by other components. Table 6-25 shows steering column performance ("success" or "failure") under heavy load, by PDOF.

At 12:00 PDOF, there were 319 MDAI cases which met the "heavy load" criteria - this is 24 percent of all of the 12:00 impacts in Table 6-24. At 11:00 or 1:00 PDOF, there were only 138 cases involving heavy loading of the column - this is just 15 percent of the 11:00 and 1:00 impacts in Table 6-24.

TABLE 6-24

SHEAR CAPSULE SEPARATION* BY PDOF BY EAD TYPE, FRONTAL CRASHES** IN WHICH DRIVERS CONTACTED WHEELS OR SPOKES, MDAI

EAD Type PDOF	% of Cases with Inches of Compression 0	 0.1-0.9	 1.0-2.9	 3.0+	N of Cases
Mesh column (shear caps. sep.)					
12:00	40	27	22	11	275
11:00 or 1:00	35	33	25	7	204
Ball column (shear caps. sep)					
12:00	37	28	20	15	617
11:00 or 1:00	43	33	16	8	383
Slotted column (shear caps. sep.)					
12:00	44	30	17	9	272
11:00 or 1:00	60	27	11	2	224
Grooved column (EAD compression)					
12:00	61	17	14	8	121
11:00 or 1:00	62	15	19	5	69
Slotted & mandrel (Shear caps. sep.)					
12:00	40	20	31	9	35
11:00 or 1:00	56	9	35	0	23
Steering wheel EAD (compression)					
12:00	50	32	13	5	22
11:00 or 1:00	50	25	13	12	16
ALL TYPES					
12:00	41	27	20	12	1342
11:00 or 1:00	47	29	18	6	892

* EAD compression, if not equipped with shear capsule
** 1st letter of CDC is F and 4th letter is W or N

TABLE 6-25

SUCCESSES* AND FAILURES** OF EAD COMPRESSION UNDER HEAVY LOAD, BY EAD TYPE AND PDOF, FRONTAL CRASHES*** WHERE DRIVER CONTACTED WHEEL OR SPOKES, MDAI

EAD TYPE	12:00 PDOF		11:00 or 1:00 PDOF	
	N of Successes	N of Failures	N of Successes	N of Failures
Mesh column	30	30	15	20
Ball column	91	71	30	24
Slotted column	25	37	4	29
Grooved column	9	13	3	11
Slotted jacket & mandrel	3	4	0	0
Steering wheel EAD	1	5	2	0
ALL TYPES	159	160	54	84
	(50%)	(50%)	(39%)	(61%)

* At least 3 inches shear capsule separation (or EAD compression if not equipped with shear capsule)

** Steering wheel or spokes severely deformed or broken - less than 1 inch shear capsule separation (or EAD compression if no shear capsule)

*** 1st letter of CDC is F and 4th letter is W or N

Moreover, at 12:00 PDOF, the column was successfully compressed in 50 percent of the cases involving heavy load. At 11:00 or 1:00 impact, the rate of success was just 39 percent.

In other words, drivers are considerably less likely to place a heavy load on the column in nonaxial impacts (15 percent of contacts) than in axial impacts (24 percent). If they do load the column heavily, they are somewhat less likely to compress it successfully in nonaxial impacts (39 percent) than in axial impacts (50 percent).

Table 6-25 also classifies the successes and failures by EAD type – although the numbers are too small for meaningful results on the grooved column, slotted jacket and mandrel, and steering wheel EAD. The ball column performs relatively well in both the 12:00 and 11:00/1:00 crashes, with more successes than failures. The Ford slotted column, while performing adequately in 12:00 crashes, does poorly in the nonaxial impacts – only 4 successes in 33 cases. The EAD column vehicles in Gloyns' sample were of the slotted type [29]. Perhaps this was a contributing factor to the inferior nonaxial crash performance of the column EAD in his studies.

6.5.3 Summary

The MDAI data in combination with the earlier studies appear to support the following conclusions, some of which must be considered speculative in nature:

- The energy absorbing devices installed in response to Standard 203 compress successfully and provide occupant protection in a large number of crashes (as evidenced by Tables 6-21 and 6-23).

- The EAD does not achieve its full occupant protection potential because it often fails to collapse under heavy load (as evidenced by Table 6-23). This problem, however, has been exaggerated in some reports by including among the "failures" many cases in which drivers did not heavily load the columns.
- Binding (noncompression) of the column is the result of nonaxial loading, which can occur because of vehicle damage, unfavorable driver kinetics, upward column rotation, unfavorable steering wheel spoke alignment, or nonaxial crash forces. Usually, these factors act in combination to produce binding (as evidenced by the work of Gloyns et al. [30], Garrett & Hendricks [28]). Downward column rotation may enhance compression.
- There do not appear to be overwhelming differences in the performance of alternative EAD designs (as evidenced by the MDAI data).
- Shear capsule separation is a relatively good measure of column collapse due to occupant load (as evidenced by Table 6-22).
- Simply changing the PDOF (with all other factors equal) has a moderate effect on column performance, but most binding is due to other causes (as evidenced by Table 6-25).
- An improved compliance test for Standard 203 - a test that would detect tendencies of a column to bind in highway accidents - may have to simulate several major sources of binding: the effect of inital vehicle damage, above all, but also the effect of different driver impact angles (vertical and horizontal) and steering wheel spoke alignments (as evidenced by the work of DuWaldt [15], Gloyns [30], Garrett and Hendricks [28]).

6.6 Effectiveness of Standards 203 and 204 by PDOF

In Section 6.5 it was demonstrated that nonaxial crash forces (PDOF other than 12:00) aggravate the tendency of the column to bind. As a result, lower effectiveness for Standards 203 and 204 would be expected with nonaxial PDOF (see, for example, Figure 3-34).

The NCSS effectiveness results are consistent with the findings on column compressibility. Table 6-26 shows that Standards 203 and 204 reduced by 39 percent the rate of fatal or hospitalizing steering assembly contact injury in 12:00 impacts. The injury reduction was only 12 percent in crashes with nonaxial PDOF (10, 11, 1 or 2:00).

These results are not quite as conclusive as they seem. The injury reduction in crashes with nonaxial PDOF is subject to large relative error because there are so few steering assembly contact injuries: Table 6-26 shows a pre-Standard injury rate of 1.59 percent in nonaxial crashes, versus 4.37 percent in axial crashes. As a result, the Likelihood-Ratio Chi-Square term for the 3-way interaction of Standard compliance x injury x PDOF was just 2.66. In other words, the observed differences of effectiveness are "not quite" statistically significant.

TABLE 6-26

FATAL AND HOSPITALIZING STEERING ASSEMBLY CONTACT INJURY REDUCTION, BY PDOF, NCSS

PDOF	Pre-Standard N	Pre-Standard % with Fat/ Hosp. Steer. Inj.	Post-Standard N	Post-Standard %with Fat/ Hosp. Steer. Inj.	Reduction for Post-Standard
12:00	2195	4.37	16,390	2.68	39%
10,11,1 or 2:00	1756	1.59	15,269	1.40	12%

The very low steering contact injury rates in nonaxial crashes, both pre-Standard and post-Standard, are consistent with the finding in Section 6.5.2 that heavy loading of the steering column by the driver is uncommon in crashes with nonaxial PDOF. Most of the steering assembly contact injuries occur in 12:00 crashes: 77 percent of the injuries in the pre-Standard cars and 67 percent in the post-Standard cars. As a result, the potential benefit of improved performance of Standards 203 and 204 in crashes with nonaxial PDOF is somewhat limited.

6.7 Effectiveness of Standards 203 and 204 by Delta V

The equipment installed in response to Standards 203 and 204 is designed to provide some protection at many levels of Delta V: at low speeds, the steering wheel padding, removal of horn rings, etc., should prevent some injuries. At medium speeds, driver load on the steering assembly becomes large enough to compress the EAD. At high speeds, Standard 204 reduces intrusion and its harmful consequences.

In 1971, Levine and Campbell analyzed North Carolina State data, which includes police-reported travelling speed among the variables [44]. The highest effectiveness for Standards 203 and 204 was observed in car-to-car frontal impacts with "medium" travelling speeds (30-49 mph). It is not possible to relate police-reported travelling speed to Delta V, but the general implication of Levine and Campbell's study is that effectiveness is highest at the middle of the severity range (Delta V = 10-20 mph).

The NCSS data do not exhibit any significant trend of Standard 203/204 effectivenesss as a function of Delta V. Table 6-27 shows that the observed effectiveness of the Standards is 34 percent in frontal crashes with Delta V less than 10 mph; it is 32 percent in crashes with Delta V 10-19; 44 percent at Delta V 20-29;

and again 32 percent for Delta V 30 and above. "Effectiveness," as usual, means the reduction of the fatal or hospitalizing steering assembly contact injury rate. There are no statistically significant differences between the effectiveness measurements for the 4 Delta V ranges.

Inferences drawn from nonsignificant results are, at best, speculative. The apparent implication of Table 6-27, however, is that the benefits of specific equipment installed in response to the standards are not limited to certain speed ranges - e.g. the intrusion-reduction due to Standard 204 is not limited to high-speed crashes (see Section 6.1).

TABLE 6-27

FATAL AND HOSPITALIZING STEERING ASSEMBLY
CONTACT INJURY REDUCTION, BY DELTA V, NCSS

Delta V (mph)	N	% with Fat/Hosp	N	% with Fat/Hosp	Reduction for Post-Standard
1 - 9	934	0.54	7651	0.35	34%
10 - 19	1122	2.67	8657	1.83	32%
20 - 29	254	13.39	1734	7.50	44%
30 +	72	27.8	698	18.8	32%

6.8 Effectiveness of Standards 203 and 204 by damage location

L. M. Patrick [65] and Garrett and Hendricks [28] both emphasized the effect of vehicle damage location on steering column performance. Their assessments were based on review of in-depth accident investigations. Exterior vehicle damage can result in damage or movement of the steering gearbox, which in turn can produce column binding, intrusion, or rotation. To a lesser extent, eccentric damage (axial forces not aligned with the car's center of mass) can induce vehicle rotation and modify the driver kinematics relative to the vehicle. Thus, eccentric damage should impair column performance because of binding, lateral intrusion of the column, or because the driver contacts the steering wheel off center. Both studies stated that column compression is especially impaired when the damage is at the right front of the car, since this introduces the largest moment with respect to the steering column.

The NCSS sample of pre-Standard crashes is, unfortunately, too small to provide statistically significant results on column effectiveness by damage location. Table 6-28 examines fatal and hospitalizing steering assembly contact injury rates by damage area. It is limited to crashes with frontal damage and 12:00 PDOF, in order to filter out the effect of PDOF on injury reduction. (Since nonaxial PDOF itself impairs column performance and also is often associated with eccentric damage, the failure to exclude cases with nonaxial PDOF would result in spuriously low effectiveness observations for the cases with eccentric damage.)

Table 6-28 shows that observed effectiveness was slightly higher in crashes with basically centered damage: 48 percent when the second letter of the Collision Deformation Classification is C and 45 percent when it is D. Effectiveness is not significantly lower in the 12:00 impacts with somewhat offcenter damage (18% for FY, 46% for FZ) or even in the 12:00 impacts with damage at the left or right sides of the front of the car (29% and 36%, respectively). The drawing at the bottom of Table 6-28 interprets the second letter of the CDC; for more information, see [11].

Table 6-28 suggests that, after controlling for the effect of nonaxial PDOF, the effect of horizontal damage location on injury reduction due to Standards 203 and 204 is probably of secondary importance.

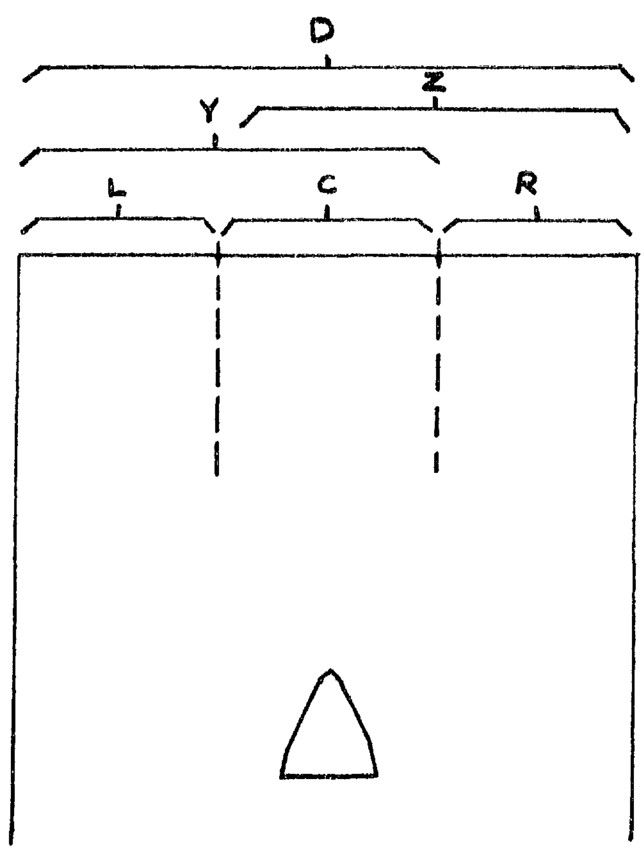
TABLE 6-28

FATAL AND HOSPITALIZING STEERING ASSEMBLY CONTACT

INJURY REDUCTION, BY HORIZONTAL DAMAGE LOCATION,

AXIAL CRASHES WITH FRONTAL DAMAGE, NCSS

Collision Deformation Classification	Pre-Standard N	Pre-Standard % with Fat/Hosp Steer. Inj.	Post-Standard N	Post-Standard % with Fat/Hosp Steer. Inj.	Reduction for Post-Standard
12 FC. . .	138	8.6	811	4.4	48%
12 FD . . .	463	5.8	3825	3.2	45%
12 FY . . .	425	4.7	2618	3.9	18%
12 FZ . . .	298	5.0	2524	2.7	46%
12 FL . . .	419	2.9	2859	2.0	29%
12 FR . . .	412	1.7	3410	1.1	36%



Garrett and Hendricks also reported that the vertical location of the damage could affect steering column performance. As an example they showed a severe impact with damage on the lower part of the vehicle which forced the steering gearbox upward and caused upward intrusion of the column (see Figure 3-33).

Exceptionally low or high damage location is not common, however, in highway accidents. The NCSS file is a probability sample. Only 10 percent of the frontal impacts on NCSS have an unusual vertical damage location (3rd letter of the CDC is not E). The observed effectiveness in those cases is the same as in the 90% of NCSS with ordinary vertical damage location: 33 percent.

6.9 Effectiveness of Standards 203 and 204 by driver age, sex, belt usage, vehicle weight and impact type

No statistically significant differences in the effectiveness of Standards 203 and 204 were found between younger and older drivers in the NCSS data, nor between males and females, belt users and nonusers, etc. The observed injury reductions were the following:

The Standards were observed to reduce injuries for drivers under 40 by 38 percent; for drivers age 40 and up, by 21 percent. The injury reduction for males was 29 percent; for females, 47 percent. The differences of observed effectiveness are well within the confidence bounds that could be expected if NCSS is split into subsamples. Moreover, the differences do not follow a consistent pattern: for example, if effectiveness had been lower for older drivers and females, it might have suggested that current energy absorbing devices are too stiff. In short, the observed nonsignificant differences should be attributed to sampling error.

Energy absorbing column performance was found to be enhanced if the driver wore a lap belt (see Figure 3-32). The lap belt enables the driver to contact the steering wheel at an angle that is conducive to column collapse. It also keeps his abdomen away from the steering wheel. In pre-Standard cars, on the other hand, a lap belt will not keep the driver away from an intruding column.

Levine and Campbell found Standards 203 and 204 to be equally effective for belted and unrestrained drivers [44]. In other words, the use of a lap belt does not "dilute" the effectiveness of Standards 203 and 204.

The NCSS data are consistent with the position that belt usage does not detract from the effectiveness of the Standards and perhaps enhances it. The observed effectiveness of Standards 203 and 204 was 29 percent for unrestrained drivers and 71 percent for lap belted drivers. The latter statistic is based on a very small sample of belt users in pre-Standard cars and is not significantly higher than the effectiveness for unrestrained drivers. Effectiveness could not be calculated for lap/shoulder belted drivers because pre-Standard 203/204 cars were generally not equipped with shoulder belts.

The observed effectiveness of Standards 203 and 204 in small cars (less than 3500 pounds) and large cars was identical in NCSS: 33 percent.

The observed effectiveness of Standards 203 and 204 in collisions of passenger cars with vehicles of similar size (cars and light trucks) was 27 percent. The effectiveness in collisions with much larger vehicles (large trucks, buses and trains) and fixed objects was 36 percent. The small difference in effectiveness is not statistically significant and suggests that the type of vehicle or object struck has relatively little to do with the effectiveness of Standards 203 and 204.

6.10 Summary: why Standards 203 and 204 have been effective

- Reduction of rearward intrusion has been the most successful accomplishment of the equipment installed in response to Standards 203 and 204. Crash test and accident data presented in Section 6.1 show that the threat of rearward intrusion has been reduced by 2/3 or more. The intrusion reduction due to Standard 204 was shown in Section 6.1 to account for 1/3 to 1/2 of the overall injury reduction attributed to Standards 203 and 204 and an even larger fraction of the fatality reduction.

- The successful compression by the driver of energy absorbing devices installed in response to Standard 203 has resulted in a significant reduction of injuries and fatalities. The evidence that the EAD collapses successfully in many highway accidents was presented in Section 6.5. The resultant injury reduction has been shown by in-depth investigation, laboratory testing, overall serious injury reduction in nonintrusion cases and the successful reduction of chest injury (Section 6.3). The energy absorbing devices are the primary reason for reduction of torso injuries not associated with intrusion: they account for 1/4 to 1/3 of the overall injury reduction attributed to Standards 203 and 204 and an even larger fraction of the fatality reduction.

- The improvements to the steering wheels that manufacturers made at approximately the time that Standards 203 and 204 took effect – padding, removal of horn rings, stronger rims and spokes, covering of the hub, smaller diameter rims – have substantially reduced head and arm injuries. (See Section 6.3.) They have also contributed indirectly to the effective operation of the energy absorbing column, preventing chest and abdominal injury. The head and arm injury reduction due to improved steering wheels accounts for about 1/3 of the overall injury reduction attributed to Standards 203 and 204, but a much smaller fraction of the fatality reduction.

- The most severe shortcoming of the equipment installed in response to Standards 203 and 204 has been the well-documented (Section 6.5) failure of the energy absorbing devices to collapse under driver load in many highway accidents. It is also the area of largest potential improvement. Since the column collapses successfully under heavy driver load only about ½ of the time, and since torso injuries not associated with intrusion account for ½ of the more serious steering assembly contact injuries, the overall benefits of Standard 203 and 204 could potentially be increased by 1/3 by the development of a column that resists binding. The principal causes of column binding – various sources of nonaxial force – are discussed in Section 6.5.

- Although Standard 204 has successfully reduced rearward intrusion, it has not prevented upward intrusion. It was shown in Section 6.1 that gross upward intrusion is sometimes directly associated with injury. The indirect association is also serious: small amounts of upward translation or twisting of the column may result in its noncompression under driver load (Section 6.5)

- The improvements of the steering wheels were, to a large extent, not required for Standard compliance and were not uniformly implemented.

Some post-Standard steering wheels offer a much better arrangement of spokes and padding than others.

- None of the energy absorbing devices on current automobiles appears to be substantially more effective than others or to display substantially better compression characteristics (Section 6.2 and 6.5).

- The negative secondary effects of Standards 203 and 204 - increased injury risk from components other than the steering assembly - are negligible (Section 6.4).

- An improved compliance test for Standard 203 - a test that would detect tendencies of a column to bind in highway accidents - may have to simulate several major sources of binding: initial vehicle damage, nonaxial driver impact angles (horizontal and vertical), and unfavorable steering wheel spoke alignment (Section 6.5).

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APPENDIX A: SAS AND BMDP PROGRAMS USED TO CREATE WORKING FILES

1. SAS program to create NCSS working file for Standards 203 and 204

```
DATA CHUCK0; SET NCSS.PREAPRIL;
IF (VGADPR EQ 'F' OR VDOFPR=1 OR 11 LE VDOFPR LE 12) AND SEATAREA=1 AND
LOCATION=1 AND VTOWED=1 AND VCASIND=1 AND NODATAIP=0 AND 10 LE VMDLYR LE 80;
SCINT=0; IF VINTRUS=1 OR VINTRUS=3 THEN SCINT=1;
IF 8 LE VINTRUS LE 9 THEN SCINT=.;
OTHERINT=0; IF 2 LE VINTRUS LE 3 THEN OTHERINT=6;
IF 4 LE VINTRUS LE 5 THEN OTHERINT=7;
IF VINTRUS=6 THEN OTHERINT=13; IF VINTRUS=8 THEN OTHERINT=28;
IF VINTRUS=9 THEN OTHERINT=.;
DV=DVTTRA1; IF DVSTRA1=9 THEN DV=DVTDAM1;
IF RESTRINV=0 OR RESTRINV=8 THEN GOTO B0;
IF 1 LE RESTRINV LE 7 THEN GOTO B1;
IF RESTRINT=0 OR RESTRINT=8 THEN GOTO B0;
IF 1 LE RESTRINT LE 7 THEN GOTO B1;
IF RESTRPOL=0 OR RESTRPOL=8 THEN GOTO B0;
IF 1 LE RESTRPOL LE 7 THEN GOTO B1;
BELTS=.; GOTO B2;
B1: BELTS=1; GOTO B2;
B0: BELTS=0;
B2: KEEP TEAM YEAR MONTH DAY SEQ RURALURB TYPEIMPA VMAKE VMODEL VMDLYR
NUMVEHIN
VVEHWT VCONTPR VDOFPR VGADPR VSHLPR VSVAPR VTDDPR VEXTEP SCINT DV OTHERINT
WEIGHTFA AGE SEX BELTS RESTRINV INJSEVER NCSSCLAS BODYREG1 CONTACT1 LESION1
SYSTORG1 AIS1 BODYREG2 CONTACT2 LESION2 SYSTORG2 AIS2 OVERALLA SEVSCORE;
DATA CHUCK1; SET NCSSPOST.ACCIDENT;
KEEP TEAM DATE SEQ NUMVEHIN CASENO RURALURB TYPEIMPA;
DATA CHUCK2; SET NCSSPOST.VEHICLE0;
IF (VGADPR EQ 'F' OR VDOFPR=1 OR 11 LE VDOFPR LE 12) AND 1 LE VBDYSTY LE 4
AND VAPPVEH=1 AND VTOWED=1 AND 10 LE VMDLYR LE 80;
KEEP CASENO VEHNO VAPPVEH VMAKE VMODEL VMDLYR VVEHWT VCONTPR VDOFPR
VGADPR VSHLPR VSVAPR VTDDPR VEXTEP;
DATA CHUCK3; SET NCSSPOST.VEHICLE4; IF V4OCSP1=11;
V4DATA=1; IF V4INTA1=4 THEN GOTO S0;
OTHERINT=V4INTA1; OTMAXINT=V4MAXE1;
IF V4OCSP2 NE 11 OR V4INTA2 NE 4 THEN GOTO S1;
SCINT=1; SCMAXINT=V4MAXE2; GOTO S2;
S1: SCINT=0; SCMAXINT=0; GOTO S2;
S0: SCINT=1; SCMAXINT=V4MAXE1;
IF V4OCSP2 NE 11 THEN GOTO S3;
OTHERINT=V4INTA2; OTMAXINT=V4MAXE2; GOTO S2;
S3: OTHERINT=0; OTMAXINT=0;
S2: KEEP CASENO VEHNO SCINT SCMAXINT OTHERINT OTMAXINT V4DATA;
```

```
DATA CHUCK4; SET NCSSPOST.SEVERITY; DVDATA=1;
IF VEHNO NE VEHNO1ST THEN GOTO D0;
DV=DVTTRA1; IF DVSTRA1=9 THEN DV=DVTDAM1; GOTO D1;
D0: IF VEHNO NE VEHNO2ND THEN GOTO D2;
DV=DVTTRA2; IF DVSTRA2=9 THEN  DV=DVTDAM2; GOTO D1;
D2: DV=0;
D1: KEEP CASENO VEHNO DV DVDATA;
DATA CHUCK5; SET NCSSPOST.OCCUPNT0; IF SEATAREA=1 AND LOCATION=1;
IF WEIGHTFA=10 AND TEAM=6 THEN WEIGHTFA=20;
IF RESTRINV=0 OR RESTRINV=8 THEN GOTO R0;
IF 1 LE RESTRINV LE 7 THEN GOTO R1;
IF RESTRINT=0 OR RESTRINT=8 THEN GOTO R0;
IF 1 LE RESTRINT LE 7 THEN GOTO R1;
IF RESTRPOL=0 OR RESTRPOL=8 THEN GOTO R0;
IF 1 LE RESTRPOL LE 7 THEN GOTO R1;
BELTS=.; GOTO R2;
R1: BELTS=1; GOTO R2;
R0: BELTS=0;
R2: KEEP CASENO VEHNO SEATAREA WEIGHTFA AGE SEX BELTS RESTRINV INJSEVER
NCSSCLAS BODYREG1 CONTACT1 LESION1 SYSTORG1 AIS1 BODYREG2 CONTACT2 LESION2
SYSTORG2 AIS2 OVERALLA SEVSCORE;
DATA CHUCK6; MERGE CHUCK2 CHUCK3 CHUCK4 CHUCK5; BY CASENO VEHNO;
DATA CHUCK7; MERGE CHUCK1 CHUCK6; BY CASENO;
DATA CHUCK8; SET CHUCK7; IF VAPPVEH=1 AND SEATAREA=1;
IF DVDATA NE 1 THEN DV=0;
IF V4DATA=1 THEN GOTO C0;
SCINT=0; SCMAXINT=0; OTHERINT=0; OTMAXINT=0;
C0: DROP CASENO VEHNO VAPPVEH V4DATA DVDATA SEATAREA;
DATA STDS.STD203;
SET CHUCK0 CHUCK8;
IF CONTACT1 NE 2 THEN GOTO SC0;
SCBODYRE=BODYREG1; SCLESION=LESION1; SCSYSTOR=SYSTORG1; SCAIS=AIS1; GOTO SC1;
SC0: IF CONTACT2 NE 2 THEN GOTO SC2;
SCBODYRE=BODYREG2; SCLESION=LESION2; SCSYSTOR=SYSTORG2; SCAIS=AIS2; GOTO SC1;
SC2: SCBODYRE=0; SCLESION=0; SCSYSTOR=0; SCAIS=0;
SC1: EAD=1;
IF VMDLYR LE 66 OR (VMDLYR=67 AND (VMAKE GE 200 OR 120 LE VMAKE LE 129))
THEN EAD=0;
IF OVERALLA=0 OR (OVERALLA=9 AND INJSEVER=5) THEN AISGE1=0;
IF 1 LE OVERALLA LE 8 OR (OVERALLA=9 AND 1 LE INJSEVER LE 4) THEN AISGE1=1;
IF 0 LE OVERALLA LE 1 OR AIS1=1 OR (OVERALLA GE 8 AND NCSSCLAS=8) THEN AISGE2=0;
IF 2 LE OVERALLA LE 6 OR 2 LE AIS1 LE 6 OR 2 LE AIS2 LE 6 OR 1 LE NCSSCLAS LE 3
OR (OVERALLA GE 8 AND NCSSCLAS=4) THEN AISGE2=1;
IF 0 LE OVERALLA LE 2 OR 0 LE AIS1 LE 2 OR (OVERALLA GE 8 AND (6 LE NCSSCLAS
LE 8 OR (NCSSCLAS=5 AND 3 LE INJSEVER LE 5))) THEN AISGE3=0;
IF 3 LE OVERALLA LE 6 OR 3 LE AIS1 LE 6 OR 3 LE AIS2 LE 6 OR 1 LE NCSSCLAS
LE 3 OR (OVERALLA GE 8 AND NCSSCLAS=4 AND INJSEVER=2) THEN AISGE3=1;
AISFAT=0; IF 1 LE NCSSCLAS LE 3 THEN AISFAT=1;
```

2. Some of the contact points were inadvertently removed from the NCSS master file used in Program 1. This program retrieves these contact points from an earlier NCSS master file and writes them onto the working file created in Program 1.

```
DATA CHUCK1; SET CON.FRBLTU;
IF 10 LE UMDLYR LE 78 AND YEAR=7 AND MONTH LE 7 AND SEATAREA=1 AND
LOCATION=1 AND (UGADPR='F' OR UDOFFPR=11 OR UDOFFPR=12 OR UDOFFPR=1);
IF MONTH GE 3 OR TEAM=3 OR TEAM=7 THEN GOTO C0;
IF MONTH=1 AND 1 LE TEAM LE 5 THEN GOTO C0;
IF 6 LE CONTACT1 LE 17 THEN CONTACT1=CONTACT1 - 5;
IF 6 LE CONTACT2 LE 17 THEN CONTACT2=CONTACT2 - 5;
IF 18 LE CONTACT1 LE 25 THEN CONTACT1=CONTACT1 - 3;
IF 18 LE CONTACT2 LE 25 THEN CONTACT2=CONTACT2 - 3;
C0: CON1=CONTACT1; CON2=CONTACT2;
KEEP TEAM MONTH SEQ UMAKE CON1 CON2;
PROC SORT; BY TEAM MONTH SEQ UMAKE;
DATA CHUCK2; SET MSTR. STD203; IF YEAR=7 AND MONTH LE 7;
DROP SCBODYRE SCLESION SCSYSTOR SCAIS;
PROC SORT; BY TEAM MONTH SEQ UMAKE;
DATA CHUCK3; SET MSTR. STD203; IF YEAR NE 7 OR (YEAR=7 AND MONTH GE 8);
DATA CHUCK4; MERGE CHUCK1 CHUCK2; BY TEAM MONTH SEQ UMAKE; IF 0 LE EAD LE 1;
IF (CONTACT1=99 OR CONTACT1=.) AND 0 LE CON1 LE 98 THEN CONTACT1=CON1;
IF (CONTACT2=99 OR CONTACT2=.) AND 0 LE CON2 LE 98 THEN CONTACT2=CON2;
IF CONTACT1 NE 2 THEN GOTO SC0;
SCBODYRE=BODYREG1; SCLESION=LESION1; SCSYSTOR=SYSTORG1; SCAIS=AIS1; GOTO SC1;
SC0: IF CONTACT2 NE 2 THEN GOTO SC2;
SCBODYRE=BODYREG2; SCLESION=LESION2; SCSYSTOR=SYSTORG2; SCAIS=AIS2; GOTO SC1;
SC2: SCBODYRE=0; SCLESION=0; SCSYSTOR=0; SCAIS=0;
SC1: DROP CON1 CON2;
DATA STDS.STD204; SET CHUCK4 CHUCK3;
```

3. It was found that the NCSS working file created by programs 1 and 2 did not contain adequate information on steering column intrusion in the post-March 1978 accident cases. This program creates a small working file of post-March cases with catastrophic or steering column intrusion.

```
DATA CHUCK1; SET NCSS.VEHICLE4; IF V4INTA1=4 OR V4INTA2=4 OR V4INTA3=4
OR V4INTA4=4 OR V4INTA5=4 OR V4INTA6=4;
IF V4INTA1=4 THEN GOTO I1; IF V4INTA2=4 THEN GOTO I2;
IF V4INTA3=4 THEN GOTO I3; IF V4INTA4=4 THEN GOTO I4;
IF V4INTA5=4 THEN GOTO I5;
SCINT=V4MAXE6; AXIS=V4MESA6; SPDM=V4SPDM6; GOTO I0;
I5: SCINT=V4MAXE5; AXIS=V4MESA5; SPDM=V4SPDM5; GOTO I0;
I4: SCINT=V4MAXE4; AXIS=V4MESA4; SPDM=V4SPDM4; GOTO I0;
I3: SCINT=V4MAXE3; AXIS=V4MESA3; SPDM=V4SPDM3; GOTO I0;
I2: SCINT=V4MAXE2; AXIS=V4MESA2; SPDM=V4SPDM2; GOTO I0;
I1: SCINT=V4MAXE1; AXIS=V4MESA1; SPDM=V4SPDM1;
I0: DROP LEVELNO YEAR MONTH DAY DATE SEQ TEAM WEIGHTFA;
DATA CHUCK3; SET NCSS.VEHICLE3; KEEP CASENO VEHNO V3CATD1;
DATA CHUCK4; SET NCSS.SEVERITY; IF DVTTRA1 GE 1 OR DVTDAM1 GE 1;
DV=DVTTRA1; IF DVSTRA1=9 THEN DV=DVTDAM1; KEEP CASENO VEHNO DV;
DATA CHUCK2; SET NCSS.VEHICLE0; IF (VGADPR EQ 'F' OR VDOFPR=1 OR
11 LE VDOFPR LE 12) AND 1 LE VBDYSTY LE 4 AND V9PPVEH=1 AND VTOWED=1
AND 10 LE VMDLYR LE 80; KEEP CASENO VEHNO VMAKE VMODEL VMDLYR VCONTPR VDOFPR
VGADPR VSHLPR VSVAPR VTDDPR VEXTEF;
DATA CHUCK5; SET NCSS.OCCUPNT0; IF SEATAREA=1 AND LOCATION=1;
KEEP CASENO VEHNO RESTRINV WEIGHTFA AGE SEX NCSSCLAS BODYREG1
LESION1 SYSTORG1 AIS1 CONTACT1 BODYREG2 LESION2 SYSTORG2 AIS2 CONTACT2;
DATA STDS.INTRUS; MERGE CHUCK2 CHUCK1 CHUCK3 CHUCK4 CHUCK5; BY CASENO VEHNO;
IF VMDLYR NE . AND WEIGHTFA NE . AND (SCINT NE . OR V3CATD1 NE .);
EAD=1; IF VMDLYR LE 66 OR (VMDLYR=67 AND (120 LE VMAKE LE 129 OR
VMAKE GE 200)) THEN EAD=0;
SCHOSP=0; IF WEIGHTFA=1 AND NCSSCLAS LE 4 AND (CONTACT1=2 OR (CONTACT2=2
AND (3 LE AIS2 LE 6 OR AIS2=AIS1))) THEN SCHOSP=1;
```

4. SAS program to create a BMDP file which was used to perform the multidimensional contingency table analyses of Chapter 5. The variable, "SCHOSP," is the injury criterion and denotes steering column hospitalization.

```
DATA CHUCK; SET STDS.STD204;
AGEGP=0; IF AGE GE 40 THEN AGEGP=1;
IF SCAIS=0 THEN GOTO SC0; IF NCSSCLAS LE 0 OR NCSSCLAS GE 5 THEN GOTO SC0;
IF WEIGHTFA GE 4 THEN GOTO SC0;
IF SCAIS=AIS1 THEN GOTO SC1; IF 3 LE SCAIS LE 6 THEN GOTO SC1;
SC0: SCHOSP=0; GOTO SC2;
SC1: SCHOSP=1;
SC2: IF SEX NE 1 THEN SEX=2;
IF SCAIS=0 THEN GOTO SC3; IF NCSSCLAS LE 0 OR NCSSCLAS GE 6 THEN GOTO SC3;
IF WEIGHTFA GE 10 THEN GOTO SC3;
IF SCAIS=AIS1 THEN GOTO SC4; IF 2 LE SCAIS LE 6 THEN GOTO SC4;
SC3: SCER=0; GOTO SC5;
SC4: SCER=1;
SC5: WTGP=0; IF VVEHWT GE 35 THEN WTGP=1;
DVGP=0; IF DV GE 15 THEN DVGP=1; IF DV=0 THEN DVGP=2;
IF BELTS=. THEN BELTS=0;
VEHOBJ=0; IF NUMVEHIN=1 OR 6 LE VCONTPR LE 13 OR 18 LE VCONTPR LE 33
THEN VEHOBJ=1;
PDOF=0; IF 10 LE VDOFPR LE 11 THEN PDOF=1; IF 1 LE VDOFPR LE 2 THEN PDOF=2;
SVA=1; IF VSVAPR='E' THEN SVA=0;
GADSHL=1; IF VGADPR='L' OR VGADPR='R' THEN GADSHL=2; IF
VGADPR='U' OR (VGADPR='F' AND (VSHLPR='C' OR VSHLPR='D')) THEN GADSHL=0;
KEEP WEIGHTFA SCER EAD SCHOSP AGEGP SEX WTGP DVGP BELTS VEHOBJ
PDOF SVA GADSHL;
PROC BMDP UNIT=3;
```

5. The BMDP file created in Program 4 does not contain the variable, "TEAM," which was later found to be an important confounding factor. This program creates another BMDP file which contains TEAM but omits the variables which were not used beyond Step 5 of the modeling process.

```
DATA CHUCK; SET STDS.STD204;
AGEGP=0; IF AGE GE 40 THEN AGEGP=1;
IF SCAIS=0 THEN GOTO SC0; IF NCSSCLAS LE 0 OR NCSSCLAS GE 5 THEN GOTO SC0;
IF WEIGHTFA GE 4 THEN GOTO SC0;
IF SCAIS=AIS1 THEN GOTO SC1; IF 3 LE SCAIS LE 6 THEN GOTO SC1;
SC0: SCHOSP=0; GOTO SC2;
SC1: SCHOSP=1;
SC2: IF SEX NE 1 THEN SEX=2;
DVGP=0; IF DV GE 15 THEN DVGP=1; IF DV=0 THEN DVGP=2;
IF BELTS=. THEN BELTS=0;
VEHOBJ=0; IF NUMVEHIN=1 OR 6 LE VCONTPR LE 13 OR 18 LE VCONTPR LE 33
THEN VEHOBJ=1;
PDOF=0; IF 10 LE VDOFPR LE 11 OR 1 LE VDOFPR LE 2 THEN PDOF=1;
GADSHL=1; IF
VGADPR='U' OR (VGADPR='F' AND (VSHLPR='C' OR VSHLPR='D')) THEN GADSHL=0;
KEEP WEIGHTFA TEAM EAD SCHOSP AGEGP SEX DVGP BELTS VEHOBJ
PDOF GADSHL;
PROC BMDP UNIT=3;
```