UM-HSRI-76-12-2
Contract Number DOT-HS-4-00942

A METHODOLOGY FOR DETERMINING THE ROLE OF VEHICLE HANDLING IN ACCIDENT CAUSATION

Final Technical Report

and

Appendix A

Duane F. Dunlap
Leonard Segel
Frederick L. Preston
Peter Cooley
Barbara C. Brown

November 1976

Prepared for the Department of Transportation, National Highway Traffic Safety Administration under Contract Number DOT-HS-4-00942. The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the National Highway Traffic Safety Administration.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
UM-HSRI-76-12-2		

4. Title and Subtitle	5. Report Date
A METHODOLOGY FOR DETERMINING THE ROLE OF VEHICLE HANDLING IN ACCIDENT CAUSATION Technical Report and Appendix A	November 1976
	6. Performing Organization Code
7. Author(s) D.F. Dunlap, L. Segel, F.L. Preston, P. Cooley, B.C. Brown	8. Performing Organization Report No. UM-HSRI-76-12-2
9. Performing Organization Name and Address Highway Safety Research Institute The University of Michigan Huron Parkway & Baxter Road Ann Arbor, Michigan 48109	10. Work Unit No. (TRAIS) 11. Contract or Grant No. DOT-HS-4-00942
12. Sponsoring Agency Name and Address National Highway Traffic Safety Administration U. S. Department of Transportation Washington, D.C. 20590	13. Type of Report and Period Covered Final 6/74-4/76 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A review of the literature on the role of vehicle handling in accident causation shows that there has been much conjecture regarding the link between vehicle handling and accidents. Little of a defensible nature is apparent other than vehicle size seems to correlate with accident experience. An examination of available mass accident data also shows this apparent size effect as well as some correlations between (1) vehicle track width and rollover accidents, (2) driver age and size of car, (3) size of car and accidents on curves, and (4) driver age and accidents on curves.

For purposes of the present study, hypotheses were developed linking vehicle handling characteristics to accident descriptors. Careful consideration is then given towards developing a statistical analysis method that would serve to support or negate such hypotheses and which would further define the amount of data required to support a given hypothesis. Implementation of the methodology to investigate the role of vehicle handling, as proposed, requires that four kinds of data be collected: exposure-to-risk data, accident data, vehicle handling descriptors, and "image risk" data. The requirement for each of these data categories is discussed at length. In addition to defining an accident data collection and analysis methodology, efforts were also devoted towards advancing the present state of the art in reconstructing the pre-crash phase of accidents and towards outlining a deterministic analysis procedure for relating vehicle handling performance directly to accident avoidance performance. The conclusions emphasize the formidable and costly nature of implementing the proposed methodology, but point up that by dovetailing efforts with other areas (of concern to accident causation analysis) agencies could substantially increase the benefit/cost ratio of follow-on research and implementation.

17. Key Words	18. Distribution Statement
Accident Reconstruction, Vehicle Handling, Statistical Analysis, Skid Marks, Vehicle Parameter Data, Accident Data	UNLIMITED

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
NONE	NONE	265	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

* U. S. GOVERNMENT PRINTING OFFICE : 1973 725-504/328

ACKNOWLEDGEMENTS

Mr. Lloyd H. Emery of the National Highway Traffic Safety Administration served as Contract Technical Manager for the research carried out in this project. His suggestions, guidance, forbearance, and most of all, patience throughout the project are gratefully acknowledged and appreciated.

As with any project of the scope and magnitude of this one, many others made significant contributions in addition to those listed as co-authors. Frank Bell was responsible for developing the vehicle parameter and performance index file, and for accessing the computerized accident data. The skid mark testing was the responsibility of Robert Wild. Thomas Gates and Mark Huber of the Multidisciplinary Accident Investigation Team at HSRI provided valuable advice and assistance in developing the vehicle handling accident report form supplement.

Ms. H. Jeannette Nafe, our secretary in the Physical Factors Group, was responsible for the fine quality of the manuscript and its numerous tables and figures.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont.)

1.0 INTRODUCTION

The research described in this report constitutes the findings from a study to develop a methodology for determining the role of vehicle handling in accident causation. To this end, a three-part methodology has been developed:

1. Data Definition, Collection, and Analysis
2. Indepth Accident Reconstruction
3. Accident Avoidance Analysis

The first topic deals with methods for uncovering statistical links between vehicle handling performance and accident experience; the second consists of detailed methods for reconstructing the pre-crash accident phase—that part where vehicle handling factors are most important; and the third is concerned with a deterministic approach to defining the influence of specific vehicle handling characteristics on accident avoidance performance.

Section 2 of the report represents an attempt to bring the task of determining the role of vehicle handling in accident causation into a realistic perspective.

Section 3 consists of a discussion of the term "vehicle handling" and offers definitions of both vehicle handling and of a "vehicle handling accident." The difficulties of identifying a vehicle handling accident are also discussed here as well as some of the problems associated with pinpointing a specific causal effect or group of effects. An extensive review of the literature on the subject of vehicle handling as an accident factor follows in Section 4. Section 5 documents information that was obtained from available accident data with respect to the accident experience of specific make/models and vehicle size categories. With the aid of information obtained from the literature review and the available accident data, a set of vehicle handling parameters and indices was selected, as described in Section 6.

Where data was available, these parameters and indices were compared with accident frequencies for various classes of accident descriptors. Ultimately, the complete set of handling parameters and indices is to be analyzed for statistical correlation with accident descriptors by applying the statistical analysis and data collection methodology described in Section 7. The developmental work carried out in pre-crash accident reconstruction is described in Section 8, while Section 9 contains a brief example of the use of pursuit-evasion methodology as a tool for determining the influence of vehicle handling properties on accident avoidance performance. Conclusions and recommendations from the study follow in Section 10.

An executive summary of the report has been bound under separate cover, as have been several associated appendices. The appendices are primarily extensions of the main sections of the report.

2.0 A PERSPECTIVE

Some maintain that research into vehicle handling as a causative factor in accidents is fruitless and therefore pointless. Others argue that even if vehicle handling factors contribute to accidents, the contribution is impossible to pinpoint and would liken the research task to a search for the Holy Grail.

If nothing else, the methodology and research findings documented in this report provide ample grounds for such sentiment, albeit with somewhat less pessimism. The difficulty in delimiting the role of vehicle handling in accident causation lies in isolating factors purely related to vehicle handling from the myriad of other factors which are also believed to be influential. It appears that a research effort sufficient to produce definitive conclusions relative to the role of vehicle handling will require expenditures of time and funds well beyond any previous effort in accident data analysis. Not only will more and better accident data be required, but data relating to (1) vehicle accident risk exposure, (2) vehicle handling performance, and (3) vehicle use patterns will also be needed. Further, in each case, the amount, accuracy, and detail of the required data will have to be an order of magnitude greater than that which has been produced to date.

The difficulty of the task ahead is partly evident in information that has already been uncovered. There is much evidence to suggest that if accident rates are considered alone (without considering confounding influences), those vehicles which are considered to be the "best handling" vehicles are the very ones that have the highest accident rates. These findings, of course, cannot be taken at face value, since it is also well known (or at least strongly suspected) that those persons who drive the "better handling" vehicles are also those who are more likely to drive in a more aggressive manner. Driving aggressiveness is just one of the confounding factors that must be accounted for, however. Among other factors there is the exposure to accident risk posed by the environment within which the vehicle is driven, the manner in which the vehicle is maintained, and the "handling performance" characteristics of the driver/vehicle system in an accident avoidance maneuver. Without exception, adequate information has not been available in previous research efforts in the amount, detail, and accuracy necessary for deriving statistically defensible conclusions. Consequently, as the literature review in Section 4 will show, many fragmentary "conclusions" have been developed, most of which are little more than conjured hypotheses. Even results from some of the best and most carefully conducted studies have proven contradictory.

To underscore this latter remark, consider some of the findings from what are unquestionably two of the best research efforts to date regarding vehicle factors in accident causation. Jones [1], in a study of the contribution of car characteristics to accident risk in Great Britain, states:

> "...accident rates are much higher for young drivers, falling to a minimum for the 34 to 54 age group and then rising again for the 65+ group."

On the other hand, Reinfurt and Campbell [2], in a study of mileage crash rates for certain car make and model year combinations, state:

> "It is not the case that lower crash rates are regularly associated with older drivers nor that higher crash rates are necessarily associated with younger drivers."

Each of these studies was carried out by competent scientists, but each arrived at seemingly opposite conclusions. Each of the authors would agree, however, that deficiencies in available data were a primary constraint on their research efforts.

The point to be made is that the methodology outlined here can be used to determine the role of vehicle handling in accident causation. Nothing short of a full-blown effort will produce the sought-after conclusions, however. A partial effort, as all efforts in the past have been, will again lead to partial and conflicting results.

BLANK

3.0 DEFINITIONS

In order to initiate the development of a methodology for determining the role of vehicle handling in accident causation, the terms of interest must first be defined. That is, what does the term "vehicle handling" mean, and what is a "vehicle handling accident." Obviously, the first term must be defined before the second.

3.1 Vehicle Handling

The first obstacle to developing a definition for the term vehicle handling is that there is little agreement, even among prominent vehicle dynamics specialists, as to what this term means. The narrowest definition would be limited only to the response characteristics of the vehicle and then only to lateral response characteristics, i.e., cornering performance. A wider definition of vehicle handling, but again restricted just to the vehicle, would include longitudinal as well as lateral response characteristics, i.e., braking and acceleration as well as cornering.

A yet wider definition would include the interaction of the driver and vehicle in jointly producing longitudinal and lateral motions. The limits of the definition here must be carefully drawn, however, in order to circumscribe that portion of the driving task which is a part of vehicle handling. As described in Appendix A, subsection A.3.2, the driving task consists of three functions: navigation, guidance, and control. Navigation includes those functions which relate to the driver's ability to plan and execute a trip. Guidance refers to the task of selecting a safe speed and planning a long-term path on the roadway in view ahead. Neither of these activities is important in relation to vehicle handling. The control actions of the driver represent the primary area of direct interaction between the driver and vehicle and hence jointly influence "vehicle handling" performance. Control actions are short-term, high-frequency activities on the part of the driver such as obstacle avoidance, directional stability augmentation, lane keeping, etc. The driver carries out these control actions by manipulating the steering wheel, throttle, and accelerator, but is yet limited by his reactions, his strengths, his relative "fit" with the work space and controls within the vehicle, and ultimately by the motions of the vehicle itself. A vehicle which corners at 0.9 g, but which permits the driver to slide across the seat in the process, is obviously not a good handling vehicle regardless of its "mechanical" cornering characteristics. Similarly, a vehicle which requires an inordinate amount of brake pedal force is in the same class. Thus, it is evident that any definition of vehicle handling must include the vehicle as well as considering the driver's control tasks.

There is yet a broader and more appropriate definition of vehicle handling, however, and this includes considerations of the road surface. All forces acting on a vehicle, other than aerodynamic forces, must arise at the tire-road interface. The friction couple at the interface effectively limits the maximum force levels.

With these thoughts, the sought-after definition takes the following form:

> Vehicle Handling - The lateral and longitudinal motion characteristics of the driver/vehicle/road-surface system in response to short-term, high-frequency control inputs.

3.2 The Vehicle Handling Accident

In light of the proposed definition for "vehicle handling," a vehicle handling accident is one wherein a deficiency in the short-term cornering, braking, and acceleration response characteristics of the driver/vehicle/road-surface system was a causative or highly contributing factor in the accident. The critical issue here is what constitutes a deficiency. If an emergency situation arises such that 0.6 g braking action would avoid the accident while the "system" is only capable of producing 0.4 g, then it is reasonably safe to say that a deficiency exists. If, on the other hand, a 3.0 g braking deceleration is required while 0.9 g is available, it is apparent that no "practical" braking action (at least within the accepted state of the art) could have avoided the accident. Thus, the definition of a vehicle handling accident must lie within the band of unsuccessful avoidance maneuvers, bounded on one side by available handling performance and on the other by performance that is practically achievable. Any accident that could have only been avoided by impractical levels of handling performance is not a vehicle handling accident. An accident that could have been avoided by practical improvements in handling performance is a vehicle handling accident.

(Judgments as to what is "practical" or "impractical" are not absolute, of course, but depend to a large extent on custom and cost considerations. For example, it is entirely possible to produce a vehicle that will develop 3.0 g's of deceleration for braking purposes, or even 5 or 10 g's. With existing rocket technology, deceleration levels are possible which are an order of magnitude greater than that available from the tire/road-surface friction couple. Within present concepts of automotive design, however, the use of retro-rockets for braking is not a "practical" consideration. Similar arguments for automatically-guided vehicles—eliminating the problem of drunk drivers—or for pre-programmed emergency maneuvers, e.g., a maneuver designed to utilize the full cornering capability of the vehicle, can also be dismissed as not being currently "practical." Thus the idea of what is practical is somewhat subjective, but in this context will be applied in terms of presently accepted design limitations.)

An accident that occurred because the complete capabilities of the "system" were not utilized could also be considered a vehicle handling accident, provided some vehicle characteristic was the culpable element. (This latter proviso would eliminate accidents involving driving-under-the-influence, but would include such possible factors as poor steering sensitivity or improper relative positioning of the brake pedal and accelerator, among many others.)

While it is natural to consider the maneuvering capabilities of an automobile in accident avoidance in the context of defining a vehicle handling accident, the definition need not be confined to maneuvering performance nor to accident avoidance alone. (The term "need not" is used here since by now it must be clear that any definition chosen will be somewhat arbitrary.) A vehicle having inadequate directional stability, i.e., one with a tendency to wander from side to side on a flat, straight road, may lead to a ran-off-the-road incident which is completely unrelated to the vehicle's dynamic maneuvering performance. A vehicle having poor directional stability would require a larger role on the part of the driver in the control task of stability augmentation. Thus, system stability as well as the dynamic response to control action should be considered in defining a vehicle handling accident.

These considerations lead to the following definition of a vehicle handling accident:

> <u>Vehicle Handling Accident</u> - An accident that could have been prevented by better vehicle handling performance where such performance could be practically upgraded by improvements in the driver/vehicle/road-surface system.

Thus, an accident is a vehicle handling accident when (A) a "system" deficiency exists, (B) that deficiency was a causative or highly contributing factor in the accident, and (C) the "deficiency" could have been eliminated on a practical basis by improvements in (1) driver skills, (2) vehicle design and maintenance, and/or (3) the road surface.

4.0 LITERATURE REVIEW

Depending on one's point of view, the literature pertaining to the role of vehicle handling in accident causation can be considered either quite extensive or extremely limited. On the one hand, considering the broad definition of vehicle handling as encompassing the influences of the vehicle, the control actions of the driver, and the road surface, the body of applicable literature is vast. Virtually every study involving these three factors could in some way be considered as contributing to the understanding of the role of vehicle handling in accident causation. On the other hand, the number of studies that purport to show a direct cause-effect relationship between vehicle handling and accident causation are quite limited. Further, with but one or two exceptions, these latter few are so lacking in objective, unbiased investigative technique as to be worthless. The first main task, then, in reviewing the pertinent literature is to delimit the range of topics and subtopics to be examined.

4.1 Scope of Review

The simple illustration shown on Figure 4.1 demonstrates the definition of vehicle handling adopted for this study. Clearly, the driver, the vehicle, and the roadway, each as separate entities, interact to influence the motions of the vehicle as it transports the driver, et al., along the roadway. The major thrust of the present study, however, is in ultimately identifying those vehicle properties which can be altered or regulated to influence the accident record. Thus, a major part of the literature review has been oriented toward material discussing (a) vehicle performance factors, (b) the vehicle/driver interface, and (c) the vehicle/roadway interface. Emphasis has been given, in all three of these areas, toward material related to accident experience. This review is presented in Appendix A. A more directed review has also been prepared which is specifically concerned with the accident causation

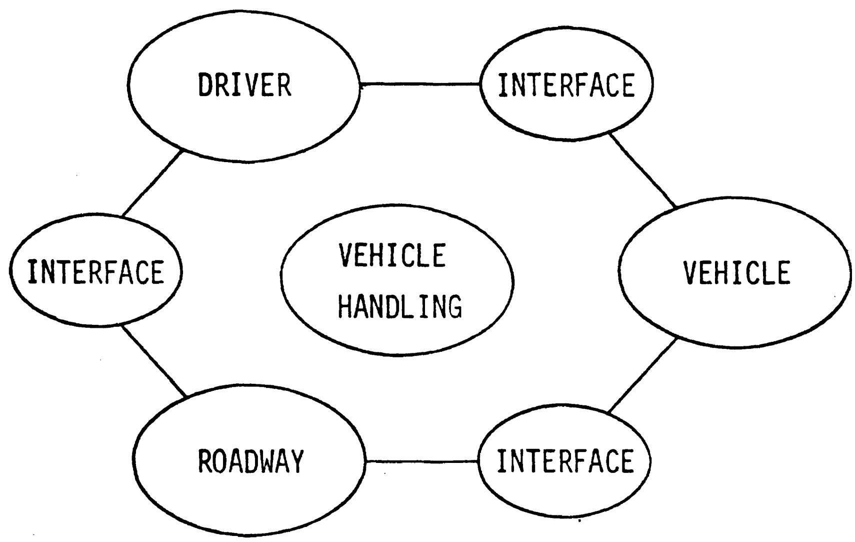

DRIVER
INTERFACE
INTERFACE
VEHICLE
HANDLING
VEHICLE
ROADWAY
INTERFACE

Figure 4.1

studies in which the role of vehicle handling is discussed. This review is presented below. Specifically excluded from both reviews is material dealing solely with the driver, the roadway, or the driver/roadway interface. Accordingly, the review in Appendix A roughly encompasses the right-half of Figure 4.1.

4.2 Accident Causation Studies—The Role of the Vehicle

Perhaps the largest problem encountered in evaluating work in this field is the tendency of investigators to find as causes those very factors which they set out to find. It has been noted, for example, that "police officers tend to equate 'traffic violation' with 'accident causation'," and their report forms reflect this by listing possible "contributing factors" that consist largely of violations (plus weather conditions). Psychologists as well "view traffic safety almost exclusively as a human problem" [3]. Other researchers commissioned to uncover the problems with alcohol, or mechanical defects, or road design discover that their pet cause is a factor in a surprisingly large percentage of accidents.

A related problem is the need felt by many investigators to attribute to every accident a single cause. This often means that as soon as a driver is identified as drunk or a tire is found to be bald, the search for causes stops [4 - 6]. For example, "the customary practice of subtracting the percentage of 'human factors' accidents from 100 percent and attributing the remainder to highway and vehicle factors is not logically defensible, since it implies a form of exclusion principle not consistent with the known facts" [7].

Obviously, the situation is far more complicated. Human, vehicular, and environmental factors combine to create nearly every accident. There are primary and secondary causes, contributing factors, and factors which increase the severity of accidents already having been "caused" to happen. These factors frequently interact in subtle ways. If an accident follows an inappropriate response by the driver, it is often arguable that a more forgiving environment, or perhaps even a more "forgiving" vehicle, might have allowed the driver to get away with his error. In such a case, where is the blame? Indeed, if unforgiving enough, the environment or vehicle might even be said to have caused the human response to have been an inappropriate one. It is quite difficult to delineate between the level of performance falling below the task demand as opposed to the task demand rising above the level of performance [3]. Kennedy [8] notes that "some of the most terrible collisions involve first-class vehicles on first-class highways, while much traveling on poor roads, sometimes in faulty cars, is accomplished safely." But this indictment of the driver is countered by the contention of Goddard and Haddon [7] that although "in some 70 percent of....fatal accidents....a small group of predominantly social and medical variables distinguish between drivers who were fatally involved and drivers who were similarly exposed but noninvolved (,this) does not imply that vehicle factors ranging from mechanical dependability to human engineering may not have also been involved in the causation of some of the same accidents."

It is therefore suggested that all studies of accident causes be viewed critically.

4.2.1 General Causal Factor Studies. As noted above, accident causation research cannot find causes for which the researchers are not looking as being significant. A large majority of studies in this area do not even consider vehicle performance or design as a possible cause. Generally, vehicle causal factors are limited to off-design performance factors alone, such as bald tires, mechanical failures, faulty brakes, or tire blowouts. This outlook clearly makes determination of the role of designed-in performance impossible.

Typical results are given in the report by Treat and Joscelyn [9] which contains a review of several additional studies. These investigators recognized the present problem by noting that, while tire blowouts and brake imbalances produce substantial evidence at the scene, steering and suspension problems may increase path deviance and decrease lateral acceleration capabilities without generating concrete evidence. They admit that "no attempt was made to account for the causal involvement of [steering and suspension systems] degradation as a source of driver fatigue and inattentiveness, or (with few exceptions) for the influence of vehicle handling characteristics arising from system design." Therefore, their results are consistent with others in the field, namely, they find steering and suspension system involvement (due to malfunction of failure) in but a few percent of all accidents. Even though the characteristics of the as-new vehicle had not been investigated as a cause, the evidence of the overall importance of vehicle performance in accident situations led the authors to recommend such research as a step towards safe handling standards.

Bundorf, in a similar study [10], notes that both vehicle design and human factors affect the control performance of the driver-vehicle system. Vehicle factors mentioned included visibility, lighting, and control locations as well as braking, acceleration, and cornering performance. The difficulty was said to lie with the fact that "the driver and vehicle....appear so interactive that at this time [1973], despite considerable effort, performance criteria for either have been very difficult to establish." The author felt that "either vehicle design factors relating to handling are not principal factors in accident causation, or they are important factors and the investigators have not learned to identify them." His own opinion was that the former hypothesis was the case. Following this contention, the author reported preliminary results on an interesting experiment. A group of thirty Sheriff's Patrol officers from Oakland County, Michigan, were given an advanced driver training course in skid control, off-road recovery techniques, controlled braking and evasive maneuvering. Over a two-year period, their accident rate was halved while repair costs per accident dropped sharply. The accident record of this group was compared to a closely matched control group of officers. The conclusion was that although the driver is most often to blame, the number of errors he would commit would decrease sharply were he merely more familiar with the performance of his vehicle. Of real interest is the magnitude of the accident rate reduction, which suggests that "handling" accidents, broadly defined, are a major portion of all highway collisions.

In a study of accidents in Monroe County, Indiana, MDAI investigations [11] involved the determination of the causal factors in 999 accidents. Vehicle factors were found to be (1) a certain, (2) a probable causal, or (3) a severity-increasing factor in 18 percent of the accidents. Contrasting with this low estimate of the involvement of vehicle factors in accident causation is an in-depth study of fifty accidents in California that occurred in 1964 [4]. The authors estimated that perhaps as many as one-fourth to one-third of all accidents have mechanical problems as contributing causal factors. Even as weakly stated a conclusion as this, however, is difficult to justify on the basis of only fifty accidents.

4.2.2 Loss-of-Control Accident Investigations. Other accident causation studies have been restricted to those categories of accidents most likely to involve vehicle performance factors as causative agents.

The California Highway Patrol investigated 5,200 single-vehicle accidents occurring in that State in September 1961 and June 1962 [5]. This study included accidents in which vehicles overturned in the roadway, struck fixed objects, or ran off the roadway without subsequent collision. Causes cited were excessive speed, alcohol or drugs, drowsiness, faulty driving, adverse conditions, distractions (inside or outside the vehicle), mechanical failure, medical problems, defective vehicle design, or other uninvolved ("unknown") vehicles. One-half of the reported single-car accidents involved severe personal injury, versus one-third of all multi-car accidents. Accidents attributed to vehicle mechanical failure or unknown vehicles were least severe, presumably due to retention of considerable control; those where the least vehicle control may be assumed, such as accidents caused by drowsiness, distractions, adverse driving conditions, or alcohol, had significantly higher percentages of fatalities.

Females were involved in a higher proportion of single-vehicle accidents than multiple-vehicle accidents, and were most likely to have been involved due to faulty driving, adverse conditions, or distractions from inside the vehicle. The authors suggested that this finding may be explained by less driving experience and fewer annual miles driven. The driver was more likely to have been male when the accident resulted from drinking, drowsiness, or excessive speed. The 15-24-year-old drivers, as a group, were involved in five times as many single-vehicle accidents as their numbers would have predicted, again pointing to the possible role of inexperience.

The fallacy of equating "single-vehicle" accidents, meaning those in which the cause was due solely to one vehicle, with accidents in which only one automobile was involved was brought out in this paper. For example, running off the road to avoid another vehicle should not be considered a single-vehicle accident from the causation standpoint. Conversely, future studies should include collisions with parked cars and head-on collisions due to one car crossing a median area.

A recent study performed in the Swedish ESV program, a joint Saab-Volvo effort, involved investigations of skidding accidents [6]. Their aim was to obtain information on (1) "typical accident situations where steerability during braking would have prevented or reduced the consequences of the accident," (2) "the proportion of the total number of accidents which are accidents depending on locked wheels," and (3) "the need of steering capacity during emergency braking." The methods employed were statistical studies of police reports, a literature survey, and interviews with representative drivers.

The police reports revealed that at least 10.5% of all accidents involved locked wheels (believed to be conservative). A further 14.3 percent were termed "loss of road adhesion" accidents exclusive of locked-wheel accidents, while an additional 21.4 percent of all accidents involved braking without locked wheels. The literature survey produced a figure for locked-wheel accidents of approximately fifteen percent of all accidents, ranging from 14.2 to 15.8 percent in the three relevant studies reported on. The driver survey found that 25 to 48% of all accidents involved emergency braking, and that locked-wheel braking usually resulted in loss of control of the vehicle, the consequences being spinning of the vehicle, deviation from the proper lane, or leaving the roadway.

Jones [12] in the United Kingdom has also been concerned with accidents in which skidding was a factor, since it has been estimated that one-third of all accidents in Great Britain are due to loss of control. Jones reported on investigations into the causes of sixty so-called loss-of-control accidents. Only eighteen could be explained solely by human error or environmental factors. Fifteen others resulted from lack of sufficient traction (either while accelerating or braking); tire defects contributed to nine of the cases; eight involved unsuccessful avoidance maneuvers without braking, and six more were attributed to other mechanical defects or failures (excluding tires and brake systems).

Of the fifteen loss-of-control accidents, at least ten involved braking, with seven cases of spinout, as happens when the rear wheels lock prior to the front wheels. Most of these cases occurred on wet roads, and six of the seven involved vehicles were lightly loaded. Two of the fifteen cases were skids due to front-wheel locking on the approach to a curve; both occurred on wet roads. There was one case in which acceleration caused loss of traction on the rear wheels and led to an accident. The rear wheel slides were judged a more serious problem due to (1) the greater instability, (2) the probability of moving into the path of oncoming traffic, and (3) the lessened occupant protection in side impacts as compared to frontal impacts.

Jones noted that present braking systems may always meet situations in which the rear wheels could lock before the front. Avoiding this behavior without the use of antilock braking systems would result in less utilization of the available tire-road adhesion and would possibly increase accidents due to front wheel lock-up during the negotiation of curves.

Another study of British skidding accidents by Grime [13] examined those environmental features which were most likely to be present at the site of an accident which involved loss of traction. The results are expressed in Table 4.1 as the relative liability of such a feature to be associated with skidding accidents; that is, the numbers represent the ratio of the frequency of occurrence of that feature at real accident sites with its frequency of occurrence at all possible accident sites.

Table 4.1 Relative Frequency of Occurrence of Roadway Features at the Sites of Skidding Accidents.

Roadway Feature	Relative Occurrence (1 = Normal)
Straight Road	1.0
Slight Curve, Radius > 500 ft.	1.8
Curve with Radius < 500 ft.	48
Slope Less Than 1:20	3.8
Slope Greater Than 1:20	13
Junction Within 50 yds.	7.3
Traffic Circle	>80
Smooth or Fine Grained Road Surface	1.5

Grime [14] also studied British accident trends from an earlier period. He examined the importance of loss of directional control as a causative factor, using three different sources of data: a set of 453 accidents between 1955 and 1962 which were investigated on the spot (biased toward severe accidents), the police reports on all 728 accidents which occurred in 1956 and 1958 on three particular trunk roads, and the reports of 188 accidents in 1961 on the M1 limited-access highway. Seventy percent of the M1 accidents (excluding those occurring at junctions) were loss-of-control accidents. Approximately 30% of the accidents on the other roads which occurred in areas without speed limits were judged to be a loss-of-control accident. Loss of control accidents made up less than 15% of the accidents in areas with a 30-mph speed limit, however.

The Highway Safety Foundation [15] studied the importance of tire tread depth in accident causation, and found strong evidence that this is a leading causation factor. Their conclusion was that the minimum legal tread depth should be 4/32 of an inch, twice that commonly recommended. An earlier study by the Foundation determined that the incidence of tires with a given tread depth on accident-involved automobiles was inversely proportional to accident experience (i.e., the smaller the tread depth, the greater the frequency of accidents). Comparisons were made by the following ratio:

$$\frac{\text{\% Accidents Involving Vehicles with a Given Tread Depth}}{\text{\% Vehicles with Given Tread Depth in General Use}}$$

The denominator statistic was determined from the Ohio Random Vehicle Inspection Program. The relative accident involvements as computed by this ratio varied in an almost linear manner from 0.54 at 12/32 of an inch to 1.92 for completely bald tires. (Tire failure was deemed to be an extremely rare cause of accidents.) There was criticism, both from public and private groups, that driver-related elements were not controlled for, specifically that those drivers with bald tires may be less responsible drivers or may, due to economic circumstances, drive older and/or more poorly maintained vehicles.

In response to the criticism, a follow-up study compared the involvement rates of the different tread depths on cars involved in accidents in which a moving violation occurred with the rates for a sample of cars that had traffic violations but no accidents. For accident-involved cars, the relative frequency ranged from 0.41 for new tires to 2.45 for bald ones, while the other group showed a range of 0.85 for new tires to 1.24 for bald ones. Presumably, this finding suggests different driver habits but still indicts low-tread tires as an accident causation factor. The trend was even more evident if only single-vehicle accidents were used in the analysis, and was strong enough that replacement of all tires at the 4/32 in. limit would actually prove cost-effective due to an estimated seven to eleven percent reduction in accidents.

4.3 Correlations Between Accident Rates and Vehicle Descriptors

It is clear that vehicle performance does vary between makes and models. If there is a connection between vehicle handling and accident experience, then some evidence of the over- or under-involvement of various makes and models ought to appear in the accident record. The primary problem in studies which attempt to gather such evidence is the need to control for the influence of other variables. Different age groups have different accident rates, so that the age distribution of the drivers of a particular group of cars must be accounted for. A car's marketing image may attract more reckless or more careful drivers from every age group, a factor for which it is nearly impossible to control. Different classes of cars may be driven a fewer or greater number of miles than average each year, or may tend to be used primarily in one kind of environment (e.g., urban, commuting, highway travel, etc.). A vehicle which tends to sustain above average damage in a given collision, or which tends to produce more serious injuries due to a poorer level of crashworthiness, is likely to have a larger percentage of its accidents reported to the appropriate authorities. All of these factors, and others, can affect the results in any study attempting to correlate accident causation with vehicle design. The literature summarized here varies greatly in the handling of these factors.

4.3.1 The United States Experience. Most of the work done in this country regarding the connection between accidents and vehicle descriptors has been the result of trying to determine either what size car is safest, or what particular makes and models are safest. Usually no attempt is made to answer the follow-up question of "Why?" Studies concerned with vehicle size will be reviewed first.

In a report by the Automotive Safety Foundation [16], the findings of separate studies of two distinctive, and opposite types of roadways were summarized. One study was based on accidents occurring on Route 66, which is largely an Interstate limited-access highway and is a wide smooth road in the sections that are unlimited-access. The risk of having a single-vehicle accident, in terms of accidents per vehicle mile, were computed for "standard" (greater than 3000 pounds in weight), "compact," and "small" (less than 2000 pounds) cars. Normalizing the results so that the risk associated with the average standard-size car is 1 yielded risks for compacts and small automobiles of 2 1/4 and 3 1/2, respectively. The addition of a trailer generally raised the single-vehicle accident rate by a factor of 4.

The second study was concerned with all accidents occurring on a 3.1-mile section of a rural California road, characterized by hills and curves, with no side markings, guardrails, or major junctions. Over a six-year period, fully one-third of all reported accidents were labeled "loss of control." Table 4.2 indicates the greater propensity of small cars to roll over, compared to larger cars. The sample size is, of course, too small to allow any quantitative conclusions.

Table 4.2. Occurrence of Rollover Accidents Versus Other Loss-of-Control

Vehicle Type	Number Rolling Over on Road	Number Rolling Over off Road	Number of Other Loss-of-Control Accidents
Standard	0	7	22
Compact	0	0	6
Small (Foreign)	4	5	9

A New York study [17] utilized data from every accident reported in that State in the first nine months of 1968, excluding those involving taxi-cabs. The data base was nearly 300,000 accidents involving approximately 550,000 vehicles, 85% of which were automobiles. The investigation was primarily concerned with injury generation, but accident frequencies were also calculated. The results showed that foreign cars were more likely to be involved in non-collision accidents (i.e., overturning, running off the road) than were domestic cars. Within both groups, compact cars and station wagons had more non-collision accidents, relative to their total accident numbers, than did large cars.

When the rear-engined automobiles and sports cars were removed from the sample, and the remaining vehicles were grouped into five weight classes, the percentage of accidents which were non-collision accidents formed a linear plot with respect to the logarithm of the average weight for each vehicle group. The results were statistically significant; the study did not, however, account for even the most basic confounding factors, particularly driver age.

In New Jersey, accident frequency data from the Garden State Parkway (limited-access) were analyzed for vehicle make, model, and size, and were compared with exposure rates from Parkway surveys [18]. The exposure survey counted 230,000 automobiles, and the accident data involved 3,400 cars. The authors compared each model's fraction of the accident-involved cars with its fraction of the cars counted in the exposure survey, and found that standard-sized (large) automobiles were <u>over-involved</u> in accidents compared to smaller cars.

The accident index computed in this report was misleading, in that the authors merely subtracted the exposure rate from the accident rate. For example, if a popular car made up 10.5% of the total vehicle population and 11.0% of the accident-involved vehicles, it was assigned an accident index of 11.0-10.5 = +0.5 (positive sign is indicative of over-involvement). Yet a rare foreign car could make up only 0.01% of the population, and have an accident rate of 0.03%, making it involved in fully three times as many accidents as its numbers would predict, and it would receive an index of +0.02. For this review, the accident index was recomputed by dividing the accident rate by the exposure rate. The positive rate exceeds the expected or predicted rate based on exposure alone; hence, an index of one is normal. Table 4.3 represents the results for the six size classes established in the report. One sees that, on this basis, intermediate-sized automobiles were safest, with safety decreasing with decreasing size. The exception to the trend was the standard-size automobile, which only bettered the mini-car category.

Table 4.3. Accident Risk Index on Garden State Parkway by Automobile Size

Size Class	Exposure Rate (%)	Accident Rate (%)	Risk Index (1=Normal)
Standard	64.34	76.05	1.182
Intermediate	13.42	6.40	0.477
Large Compact	11.73	7.43	0.633
Medium Compact	3.29	2.54	0.772
Small Compact	6.74	6.90	1.024
Miniature	0.46	0.68	1.478
Standard	64.34	76.05	1.182
All Others	35.66	23.95	0.672

Among the conclusions that can be drawn from the detailed breakdown are:

1) The expensive "luxury" automobiles had the best accident records of any standard-size cars.

2) The Chrysler Corporation intermediate and compacts were among the best of all models, despite the poor showing of that company's larger cars.

3) The small compacts and foreign cars did not exhibit a clear trend that might suggest that price or performance is a factor in accident causation.

Case, et al. [19], used owner surveys to try to determine the relative safety of different size cars in California. They asked the owners of two different makes of economy cars, two different domestic compacts, and two full-sized cars to answer questions about their age, sex, annual mileage, etc., as well as their accident records. Only 31% of the addressees responded to the mailed questionnaires, so the results are not fully representative. Table 4.4 gives the computed accident rates, as well as information about

Table 4.4 Accident Rates and Age Information for Six Automobile Makes, Based on California Survey of 8900 Owners.

	Economy		Domestic Compact		Full-Sized	
	Volkswagen	Toyota	Falcon	Nova	LTD	Pontiac
# Acc./ 10^5 mi. (All Ages)	0.971	0.971	0.985	0.958	0.730	0.763
Percent of Drivers Under 20 Yrs. of Age	4.5	3.0	2.0	2.0	0.5	0.2
Mean Age of Drivers	33.5	39.2	49.3	44.7	48.7	49.3

the age of the drivers of each automobile make. The trend toward fewer accidents in large cars is visible, but when the results were normalized for the various driver characteristics, no consistent trends remained.

This same report cited a 1961 study, also done in California and summarized in Table 4.5, as well as an Illinois study from that

Table 4.5. 1961 California Accident Involvement Comparison, by Size of Car

Vehicle Size	Percent of All Registered Vehicles	Percent of all Accident-Involved Vehicles
Compact	9.70	5.69
Economy	6.58	5.59
Sport	1.47	1.69
Standard	82.25	87.03

same period. Both reports found that the smaller cars were under-involved in accidents, even before corrections for driver age were made, and that they were very under-involved in pedestrian accidents. The California research did indicate, however, that the smaller vehicles had a poorer record with respect to loss-of-control accidents.

The most recent writing on the subject of safey versus size is the article by Hart [20]. Citing the already-mentioned California and New Jersey works, as well as other reports, Hart concluded that, from the point of view of society as a whole, "small cars are much safer than large cars." His summary of the problem states that

> "1) Large cars are involved in multi-car collisions more often than small cars in relation to their exposure."

"2) Large cars are involved more frequently in pedestrian accidents.

3) In collisions involving both large and small cars, the driver of the large car is more often at fault." Large cars are most likely to cause accidents by infringement upon the road rights of other vehicles; the small car is more likely to have caused an accident because of excessive speed.

"4) Although small cars have a higher involvement in single-vehicle accidents, they are burdened (a) by a high proportion of accident-prone (under 25) drivers, (b) by instabilities which are not size related, and (c) by inclusion of the sport cars in that category."

The author suggests that the available data understates the small cars' advantages because their involvement rate is inflated by the collisions with large cars which are the fault of the large cars' drivers. He then offers possible reasons for this differential accident rate:

1) Large cars make larger targets and/or projectiles in accident situations.

"2) American cars (which comprise all of the standard class) appear to have softer suspensions. These softer suspensions may increase the probability of loss of control in emergency situations."

"3) Longer, wider hoods decrease visibility."

4) Driver error may become more likely as vehicle size increases, due to the discrepancy in size between the driver and his vehicle.

5) More large cars may be defective due to their higher repair and maintenance costs.

As far as the question of accident involvement versus vehicle make and model is concerned, the only comprehensive work that may be added to the New Jersey investigation is an analysis by Milie [21]. This research used reports on 700,000 accidents in New York State in 1969 and 1970. Exposure was accounted for by determining the number of vehicle registration months for each make and model of automobile. Because accidents are only reported for damage exceeding a certain fixed amount, and because newer and more expensive automobiles are more apt to be properly repaired with new parts with the resulting increase in reported numbers of minor accidents, the author compared models within the same size and value categories only.

The accident rates were weighted to account for driver age and sex. The standardized rates showed far less dispersion than the raw data alone.

The New York data, although not limited to turnpike accidents, should have compared well with the New Jersey figures. It did not. The New York records showed the safest compact, intermediate, and luxury cars to be Falcon, Fairlane, and Chrysler, respectively; the Chrysler faired poorly in New Jersey, while the other two were about average. The New Jersey study, admittedly not normalized for driver variables, showed large model-to-model variations, even within size classes where driver effects are likely to be equal. The New York report found no statistically significant differences between models within a class.

In addition to investigations of the effect of size or make, other investigators have examined particular vehicular design characteristics for evidence of their role in accident causation. Another study of New York State accidents compared front-engined compact cars to those with rear-mounted engines [22]. The results seem to dispute all of the feelings that rear-engined cars are unsafe due to their inherent handling problems. The accident involvement rates were computed as accidents per 100,000 vehicle registration months, and were kept separately for different age groups. Table 4.6 shows the important results, which are summarized as follows:

1) Domestic front-engined automobiles had a higher accident involvement rate than domestic rear-engined cars (specifically Corvair).

2) Front-engined cars as a group had a higher involvement rate than rear-engined cars.

3) Foreign front-engined cars had a higher rate for one age group; the differences were not significant for other ages.

Another study of the contribution of vehicular factors to accident causation was concerned with the stability of rear-engined cars. Hoffmann [23] relied upon the work of others in concluding that "there is some evidence from accident statistics... that certain types of vehicles have control problems. These problems are shown by the large number of single-vehicle 'ran off roadway' and 'rollover' accidents which they have (when) compared with other vehicles." Several studies are cited which agree that rear-engined swing-axle cars roll over much more frequently than large, conventional sedans. It is speculated that limit oversteer may lead to a sideways sliding at the limit, instead of frontwards plowing, and that this might leave the vehicle more prone to tripping by curbs. It is also noted that swing-axle suspensions generally do not actually jack-up or tuck under until approximately 0.7 g's lateral acceleration is reached, making this feature a most unlikely cause of many accidents.

The last several reports reviewed here are concerned with vehicular factors other than performance. The purpose of the review is to illustrate the magnitude of the problem of controlling for independent variables. The earliest, by Schreiber [24], found that 1960 accident reports on fleet-owned automobiles revealed a

Table 4.6. Accidents per 100,000 Vehicle Registration Months for Domestic and Foreign Automobiles by Engine Location and by Driver Age.

Automobile Type	Driver Age	Accident Rate
	16-29	52.9
Foreign front-engined	30-54	24.2
	55-89	15.5
	Total	35.6
	16-29	40.9
Foreign rear-engined	30-54	23.7
	55-89	13.4
	Total	28.6
	16-29	50.5
Domestic front-engined	30-54	32.4
	55-89	29.5
	Total	34.6
	16-29	37.4
Domestic rear-engined	30-54	20.3
	55-89	15.2
	Total	23.7

difference in accident rates among three similar (but unidentified) makes. More significant variations were found between those cars with radios, or with power steering, and those without, however. Both of these options led to higher accident rates.

Another more recent investigation [25] found that Department of Transportation regulations governing vehicle lighting, windshield-washing, and braking systems performance have reduced accident occurrences by a minimum of one percent to a maximum of nine percent, depending on the accident causation data one chooses to believe.

Finally, a Massachusetts study of Pinto and Vega accident statistics revealed another pit-fall [26]. The accident rate for the 1970-71 combined calendar years was 37% higher for the Vega than for the Pinto when calculated by dividing the number of accidents in that period by the number of registered vehicles at the end of the period. Driver variables, weather conditions, and accident type could not offer any clues as to the reason. It was discovered, however, that Vega sales had risen sharply following a long strike at introduction time in 1970, and that using vehicle registration months as an exposure index eliminated the differences in the two models' rates.

4.3.2 The British Experience. A somewhat dated study provides an example of failure to control for even obvious influential factors. Giles and Sabey [27] used data on all fatal and serious accidents in Great Britain in 1956 to compile the figures shown in Table 4.7. The data seem to indicate that increased power and performance leads to a greater propensity to skid. This same study, however, produced the statistics in Table 4.8 using 1957 data. The later data show that younger drivers have more skidding accidents, yet the authors did not correct the vehicle data for the age of the drivers involved. Furthermore, the horsepower-to-weight ratio would be a more logical variable than engine capacity,

Table 4.7. Percentage of Accidents Which Involved Skidding, by Engine Size.

(1956 Fatal and Serious Accidents Only, in Great Britain)

Engine Capacity	% Skidding - Wet Road Accidents	% Skidding - All Accidents
Less than 800 cc	17%	12%
800-900 cc	15%	12%
900-1000 cc	17%	12%
1000-1200 cc	19%	15%
1200-1400 cc	21%	16%
1400-1500 cc	22%	17%
1500-1600 cc	22%	19%
1600-1800 cc*	(17%)	(16%)
1800-2600 cc	24%	21%
Greater than 2600 cc	28%	21%

*This class contains no vehicles registered after 1949.

Table 4.8. Percentage of Accidents Which Involved Skidding, by Driver's Age

(1957 Fatal and Serious Accidents Only, in Great Britain)

Age	Dry Roads	Wet Roads	Icy Roads	All Conditions
Under 20	9%	21%	67%	14%
20-24	7%	20%	65%	12%
25-29	7%	15%	46%	11%
30-39	6%	12%	42%	9%
40-49	5%	8%	47%	7%
50-59	4%	10%	22%	7%
60-69	2%	3%	22%	3%
Over 70	4%	0%	0%	4%

as larger cars may actually be under-powered relative to small ones despite having larger engines; another possibility is that the larger cars may have more skidding accidents because their size has degraded their handling qualities. Finally, by not examining actual accident causes, the possibility has been left open that higher speeds on the part of the more powerful cars led to skidding in turns or while braking, in which case human decision making and not design per se is at fault. The complications involved in reaching honest conclusions about the role of performance in accident causation quickly become almost overwhelming.

(At this point, it is pertinent to observe that the use of such figures as "the percentage of all accidents for the given vehicle type which involved the characteristic under study" can mask the effect of characteristics not under study. For example, if an unusually high percentage of the accidents incurred by a specific vehicle involve skidding on curves, the truth may be that the handling is normal but exceptional brakes have led to fewer than average collisions at intersections. Because percentages must add up to one hundred, it is preferable to rely on "number of such accidents per 10^8 vehicle-miles," or some similar statistic, whenever possible.)

Another early study (in the 1960's) used data from accidents which were personally investigated by the author [28]. His results were put forth cautiously, and again were not well controlled for the age or sex of the driver, or for miles driven. The number of steering turns lock-to-lock was not found to be a predictive design factor, but vehicle weight was, with the heaviest cars having more accidents. Low power-to-weight ratio seemed to lead to fewer accidents, although the results were not conclusive and were not controlled for total vehicle weight, vehicle usage, etc. The author cited an American study, which indicated, instead, that a higher power-to-weight ratio, up to a point, was safer.

A 1969 study of over 600 accidents [29] was carried out in a manner similar to the MDAI studies in this country wherein accident-involved vehicles were examined to determine the exact accident cause. In addition to physical factors such as brake deficiencies or bald tires, the vehicle age, make, mileage, speed and load were recorded. Cars with less than 10,000 miles on their odometers were found to be under-involved, while cars with over 40,000 miles were over-involved in accidents. Contributing factors might be driver characteristics or maintenance records, as well as vehicle design. Confirmed vehicle causal factors included brake factors (in 5% of the vehicles) and excessive steering-wheel play (3%). Obstruction of forward vision contributed to 17% of the accidents, and smooth tires to 5%. Of interest is the fact that 25% of the accident-involved vehicles <u>and</u> 25% of all vehicles (according to a random survey) had at least one smooth tire, yet the in-depth investigations showed smooth tires to be a small factor in accident causation. Tire pressure deficiencies were more common in the accident-involved group than in the control group, and were estimated to have contributed to a minimum of 7% of the accidents.

The part of the report of main interest to this review is the comparison of accident rates by vehicle make (although not by model) displayed in Table 4.9. Here, the percentage of accident-involved cars from each manufacturer is compared with the percentage of cars, in an exposure survey, made by the same manufacturer. Without corrections for driver age, it is not surprising that the most expensive car (Jaguar) was the only one significantly under-involved, since its drivers are likely to be much older than average.

The most recent results from Great Britain, however, are included in a series of studies by I.S. Jones, all directly related to the problem of determining the true extent to which vehicle handling characteristics affect the accident rate.

The first report was based upon the information from questionnaires sent to purchasers of a particular brand of seat belt [30]. The sample was obviously not representative: urban areas

Table 4.9. Accident Involvement Versus Exposure for Automobiles of British Manufacture.

Vehicle Make	Percentage of All Urban Accident Involved Cars	Percentage of All Rural Accident Involved Cars	Percentage of All Cars, as Estimated by Exposure Survey
BMC	45.5%	47.8%	49.2%
Ford	24.1	23.0	22.3
Rootes	8.8	8.4	9.2
Vauxhall	6.4	3.9	7.5
Std. Triumph	6.2	6.2	5.8
Jaguar	2.3	3.4	12.5
Rover	1.3	2.2	1.7
Foreign	2.6	3.9	2.3
Misc.	2.6	0.6	1.7
Not Known	0.2	0.6	0.2

were under-represented due to less belt usage, the more safety-conscious owners were more likely to respond, and of course people involved in fatal accidents were under-represented. However, the results were confidential and it was hoped that the respondents would be more truthful than when answering police investigators. It was found that rear-engined cars were less likely to become involved in rear-end collisions, but more likely to be involved in single-vehicle accidents and single-vehicle rollovers, than front-engined cars. Looking at the single-vehicle accidents alone, the rear-engined car was still the one most likely to have over-turned, with front-wheel-drive cars least likely. Because front-wheel-drive cars had more single-vehicle accidents, however, the total chance of rollover was approximately the same as for conventional (front-engined, rear-wheel-drive) cars.

A second report by Jones [31] established a relationship between measurable vehicle design parameters and frequency of overturning accidents. Because his earlier work had shown that 83% of all overturning occurs in single-vehicle accidents, he looked at single-vehicle accident data alone. In this study, Jones used as a measure of proneness to overturn, the number of single-vehicle accidents with overturning divided by the number of total single-vehicle accidents.

This measure was computed for 19 models of automobiles using the British national accident statistics from 1969 and 1970, and was broken down into rural and urban accident rates. Linear regression analysis showed that the rural accident rate correlated with the simple center-of-gravity-height/track ratio, the correlation coefficient being 0.491; the urban correlation was not significant. Since many overturning accidents follow contact with abrupt changes in ground contour, the author used a simple model of an automobile-curb impact to approximately compute the minimum lateral velocity which would cause each of the 19 vehicles to overturn if tripped by a curb. This minimum velocity correlated better with the overturning probabilities from the accident statistics. The correlation coefficient was 0.66, significant at the 1% level.

The last work by Jones [1] used the same data base, but calculated single-vehicle and multiple-vehicle accident rates for 34 car models. Data from serious and fatal accidents only were employed because of the more accurate reporting procedures used in these accidents. (This restriction may have biased the sample toward fewer large cars, however, since serious and fatal accidents occur less frequently with larger cars.) Using registration figures and surveys of odometer readings, the accident rates were computed on the basis of accidents per 10^8 miles. With this accounting for exposure, the single-vehicle accident rate (presumably most strongly influenced by vehicle characteristics because of the large number of loss-of-control accidents represented) did indeed show a greater range of rates between models than the multiple-vehicle accident rate.

Since the author knew the age and sex of all involved drivers and since the overall accident rates for various age groups and for both sexes were also known, he was able to normalize the rates for age and sex. This involved the plausible assumption that the distribution of accidents among the age groups is independent of the vehicle model involved. Because car-to-car accidents are much less dependent on vehicle characteristics, Jones contends that the normalized car-to-car accident rate, with driver effects removed, accurately reflects vehicle mileage or exposure. Thus he was able to include vehicle models for which the mileage survey had not produced significant results. Table 4.10 contains the ratio of single-vehicle accidents to multiple-vehicle accidents, with the first column representing the rate without driver effects accounted for, and the second representing the rate with all driver age and sex contributions removed. The range of rates in the last column should represent the contribution of all effects other than those due to the driver.

Finally, the author compared the accident rates with known vehicle design parameters and with both objective and subjective measures of vehicle handling performance (obtained from road tests conducted and reported by motor magazines). On omitting sports cars from his sample, he found that increased vehicle weight and wheelbase resulted in fewer single-vehicle accidents. Also, cars with large amounts of understeer at zero lateral acceleration, but whose understeer decreases with increasing lateral acceleration, had the lowest single-vehicle accident rates. The rate was also shown to increase with increasing instability under severe braking. Many of these results were due, in part, to ties or interactions between the handling ratings and vehicle weight, however. This interaction or relationship between the various parameters complicates the results, but regression techniques allowed him to draw the following important conclusions:

Table 4.10. Single-Vehicle Accident Rates, With and Without Normalization for Drivers Age, for All Models of Cars Involved in British Accidents in 1969 and 1970.

Model	Code Number	Single-Vehicle Accident Rate / Normalized Car-Car Accident Rate	Normalized Single-Vehicle Accident Rate / Normalized Car-Car Accident Rate
Large Cars	1	.302	.374
	2	.516	.678
	3	.393	.408
	4	.262	.414
	5	.283	.467
	6	.308	.436
	7	.242	.340
Medium Cars	8	.383	.447
	9	.385	.464
	10	.625	.578
	11	.430	.502
	12	.224	.273
	13	.464	.526
	14	.390	.455
	15	.408	.488
Small Cars	16	.782	.695
	17	.585	.662
	18	.454	.588
	19	.564	.600
	20	.482	.453
	21	.701	.656
	22	.395	.452
	23	.600	.473
	24	.672	.515
	25	.752	.510
Sports Cars	26	1.083	.375
	27	.982	.745
	28	.800	.833
	29	1.318	1.000
	30	.776	.645
	31	.841	.693
	32	1.282	.672
	33	1.719	.694
	34	.513	.546

Age effects account for about 40%, and the proportion of male to female drivers for about 30% of the model-to-model variation in single-vehicle accident rates. The horsepower-to-weight ratio accounts for a further 13%, and braking instability for about 3%. If the driver effects are removed, then only about 35% to 40% of the remaining variation in normalized rates can be attributed to vehicle performance factors.

This latter study is probably the finest published to date on the topic of interest. Even though the results are not necessarily directly applicable to the problem in this country, it does provide an excellent example of the importance of accounting for non-vehicular effects, as well as presenting methods for how to do so.

4.3.3 Studies from Other Countries. Two research studies were found that presented accident data as evidence that vehicle performance is a factor in accident causation.

The first study [32] cites an analysis of accident data performed by a German insurance company. Table 4.11 is taken from Reference 32 and gives the relative accident involvement index, by vehicle model, for twenty models. The most striking feature are that (1) the highest involvement rates are for expensive sports cars which are generally respected for their outstanding cornering, braking, and acceleration performance, and (2) within each pair of models from one manufacturer, the faster, "sportier" model had the higher involvement rate. No information is available, however, as to how the indices were computed or whether efforts were made to control for confounding variables.

In a second study [33], the design characteristics of vehicles were examined for correlations with Australian accident data. Rates (accidents per 10^8 miles driven) of casualty and non-casualty, single-vehicle, multi-vehicle, and pedestrian accidents were compared for vehicles with different weights, horsepower, brake lining area, or ratios of these design parameters. Driver age

Table 4.11 Relative Risk of Accident Involvement by Make and Model, Based on Accident Data from West Germany.

Manufacturer	Vehicle Model	Relative Accident Involvement
Volkswagen	1200/1300	54
	K70	86
Opel	Kadett B	69
	Commodore GS Limo.	157
Ford	Taunus Turnier	70
	Capri RS/3.0 GXL	210
Mercedes-Benz	200/220	96
	600	220
BMW	1800/2000	113
	2002 ti	209
Porsche	356	204
	914	242
Fiat	500	53
	850 Spider	157
British Leyland	Morris Marina	100
	Triumph TR4/6	204
Lotus	Europa	204
Maserati	Indy	250
Lamborghini	Espada/Jarama	250
Lancia	2000 Coupe	231

and sex, day of week, occupancy level of the vehicle, and year of manufacture were also recorded. The accident data were from 1961, while the mileage survey took place in 1963 and 1964; hence it was necessary to assume that the average mileage accrued by each vehicle type did not vary significantly over that period.

When weight and power were combined as a ratio, the highest involvement indices obtained were for vehicles with medium power-to weight ratios with lower involvement being observed in all types of accidents for extremely high and low values of power-to-weight ratios.

Another significant trend was a pronounced decrease in accident involvement with an increasing ratio of area of brake lining to horsepower. For the lining area-to-weight ratio, the lowest accident involvement corresponded to the highest ratio class.

The authors speculated that some of the performance features, particularly those related to horsepower, could serve the experienced driver well while increasing the accident risk for the less experienced. Evidence points to this hypothesis being true since the highest horsepower and horsepower/weight classes, which had very low overall involvement rates, had, by far, the highest accident rates when only accidents involving drivers under thirty years of age were considered.

4.4 Concluding Remarks

It is apparent that vehicle factors do play a role in accident causation. The role is not understood; indeed, past research does not provide a means of accurately quantifying the magnitude of the role.

The works reviewed here contradict one another in many respects. While in-depth investigations have failed to identify vehicle performance as a frequent causal factor, other less direct evidence suggests that it may be. The role of driver inexperience in loss-of-control accidents is generally recognized as well as the potential for achieving safer highways by means of better emergency maneuver training. These observations indicate a driver failure problem in the driver-vehicle control system. What is not indicated is the degree to which that system's performance can be improved by changes in the vehicle alone.

Research outside the United States has indicated that tire pressure or tire condition, which affects handling almost exclusively, can cause accidents. Better braking systems have also been shown to be a path to lower accident rates. How these results apply to the type of driving situations found in the United States is not readily apparent.

Within this country, the most significant finding is that those cars with the best avoidance capabilities, particularly small cars, have serious stability problems. The vehicle classes with the lowest rates of overall accident involvement consistently fare poorly with respect to loss-of-control or single-vehicle accidents. Determining the optimal mix of small-car maneuverability and big-car stability may be the most significant impact we can make in this field.

Other work in this country tends to be largely contradictory, whether in the area of accident cause determination or model-to-model accident risk comparisons. Much of the problem is a lack of adequate data; many studies reported on too few accidents to produce meaningful results. Another aspect of the problem is a failure to account for the myriad of independent variables which make every accident unique.

One disappointing aspect of even the best research, which uses accident data to point out dangerous design characteristics, is the complete failure to ask, let alone try to answer, the question of "Why?" In many reports evidence is presented that suggests certain vehicle models are very accident-prone, or that certain general vehicle configurations are over-involved in accidents. No attempt is made to look further, however, to see if those extra, unpredicted accidents were indeed the result of vehicular factors. And even if the statistics indicate that the fault lies with the vehicle, could not the fault be poor visibility, or poor ergonomic design, or poor headlight or taillight effectiveness?

In other words, the extent of the role of vehicle performance in accident causation is not likely to be known before statistical research, vehicle testing and rating, and improved accident reporting are combined for the purpose of answering that specific question.

BLANK

5.0 EVIDENCE OF VEHICLE HANDLING FACTORS IN AVAILABLE ACCIDENT DATA

While much accident data has been collected and organized in computer files in the United States, few of these files have been examined with the idea of determining the role of vehicle handling in accident causation. One of the purposes of this work was to carry out such an examination.

At the Highway Safety Research Institute there are upwards of two hundred separate accident files which are available for research purposes. Most of these are special purpose files which have little utility in the present application. To be usable for studies of vehicle handling, the first prerequisite that an accident file must fulfill is that the accident-involved vehicles must be identifiable to a relatively fine degree. A second requirement is that the parameters describing an accident must be differentiated in such a way as to have some meaning with respect to vehicle handling considerations. A third requirement is that the data file contain enough cases to produce meaningful statistical results. Finally, the raw data must have been collected in a random fashion and must be reasonably accurate. Any derived findings would be spurious without these latter two requirements being fulfilled.

At present, there is no existing data file that satisfies all of these requirements. Two files do, however, come close enough to provide useful information, specifically, the mass-accident data files from King County (Seattle), Washington, and from the State of Texas. The results of studies in which these two files were employed to examine vehicle handling accidents will be described below. (The CPIR accident data file was also reviewed as part of this work and is also discussed here.)

5.1 The Utility of Mass Accident Data Files

As already implied, the mass accident data from Texas and Washington State represent two of the best sources of such data in the United States. In each file, the code labels describing the vehicle include make, model, and model year, but without refinements such as engine options, power versus manual steering, tire options, etc. In addition, each file contains several code labels connoting various accident event descriptors, e.g., skidding, overturning, head-on collision, avoidance maneuver, etc. Further, each file contains descriptive data on the roadway, the weather, the driver, the surrounding area, and other related information. Each file, in addition, is probably more accurate than typical mass accident data compilations due to the apparent care with which the data is treated; no information is available, however, with respect to the absolute accuracy of the data.

Differences between findings from the two data sets can be expected to arise from three areas: the differences in the vehicle populations, the driving environment, and in the kinds of accidents investigated. Certain imported vehicles are more prevalent in the Seattle area (e.g., Toyota) than in Texas, for example, and much more rainy weather occurs in Seattle. The Texas data set was restricted to single-vehicle accidents, while that from King County included both single-vehicle accidents and the striking vehicle in accidents involving two or more vehicles.

The other difference that may, or may not, influence the findings is in the definition of a "reportable accident." A "reportable accident" in Texas is one which involves death or personal injury, or a minimum property damage of $250. A reportable accident in Washington is one which involves a minimum property damage of $100.

The findings obtained from analyses of the Texas and King County accident data are summarized in the next two subsections. A third subsection follows and contains a discussion of comparisons and differences as appropriate. Appendix B presents the details of the analysis of these mass accident data.

5.1.1 Findings from the King County (Seattle) Data. The accident data file from King County (Seattle), Washington contains approximately 65,000 vehicle involvements which occurred in 1973. In analyzing the data, an attempt was made to isolate as much as possible the influences of vehicle factors on the accident record. Driver influences were considered only to the extent that the choice of vehicles by specified segments of the driving population may affect the accident record of that vehicle. Controls for exposure, whether for vehicle populations, driver populations, or the driving environment, were not considered since the required data do not exist.

The accident data set used in this investigation consisted of approximately 9,500 vehicle involvements which were filtered from the original 65,000 cases. Vehicle selection was restricted to passenger cars and included only those vehicles involved in single-vehicle accidents or which were the striking vehicle in accidents involving two or more vehicles. The data set was further limited to unimpaired drivers and to accidents occurring on wet or dry road surfaces only.

In analyzing the data set, links were examined between specific vehicle, driver, and road classifications in several categories of accidents. Some specific findings, as obtained from the King County data analyses, are:

- Vehicles having the highest frequency of accidents on curves are the sub-compact/mini and sporty models—some of these vehicles have more than twice the involvement of the total data sample.

- Accidents on wet surfaces do not show any clear trends with respect to vehicle types.
- Overturning accidents are clearly correlated with vehicle track width. The Toyota Corona—three times more involved in overturning accidents than the total sample—had the narrowest track width.
- Rear-end accidents do not strongly correlate with any particular vehicle class, although the braking performance and rear-end accident experience of the Vega and Ford Capri seem to compare well.
- "Sideswipe" and turning accidents are more prone to occur with the larger, more bulky vehicles. Side visibility, vehicle volume, and handling agility appear to be important factors in these accidents.
- The highest frequencies of skidding accidents are associated with sporty and sub-compact/mini type vehicles; the lowest are for the luxury sedan models (e.g., Cadillac).
- Speeding is heavily implicated in accidents involving super sport and European sport car vehicles; the least involved vehicles are the luxury models.
- "Failure-to-yield" and "inattention" accidents are most commonly encountered with the luxury models.
- Vehicles having the most accidents with just one occupant (the driver) fall into the personal luxury and sub-compact classes. Surprisingly, the vehicle most involved in accidents with more than one occupant is the VW—a load-related handling problem may exist here.
- Residence proximity seems to have little influence on accident experience.

- The vehicle body types most highly involved in accidents according to driver occupation are:

Professional	Luxury Sedan Super Sport
Clerical/Sales	Sub-Compact Super Sport
Skilled/Semi-Skilled Workers	Super Sport Luxury Sedan
Housewives/Domestics	Luxury Sedan Personal Luxury
Students/Children	European Sports Car Sub-Compact/Mini

- Male drivers have the highest frequency of accidents in convertibles and super sport classes of vehicles.

- The most and least involved vehicle body types by driver age are:

Age Group	Most Involved	Least Involved
15-19	Specialty/Pony	Personal Luxury
20-24	European Sports Car	Luxury Sedan
25-29	Sub-Compact	Standard/Full Size
30-34	Personal Luxury	Sub-Compact
35-39	Standard/Full Size	Super Sport
40-44	Luxury Sedan	Specialty/Pony
45-49	Luxury Sedan	European Sports Car
50-54	Personal Luxury	Sub-Compact/Mini
55-64	Luxury Sedan	European Sports Car
>64	Luxury Sedan	European Sports Car

- There is a trend through the age groups from accidents with the sporty vehicles at the younger ages, to the smaller domestic vehicles during the young family years, and to the luxury models in middle and old age.

- Drivers of smaller vehicles are more involved in accidents when wearing seat belts than are drivers of larger vehicles—an exception is the VW where seat belt usage in accident-involved vehicles is less than one-half the frequency for the total sample.
- Accidents on curved sections of road increase with the number of vehicle occupants indicating a handling and/or distraction problem.
- The most involved vehicles in accidents on curved sections of road with more than one occupant are the sub-compact and sporty types. The VW Beetle was by far the most involved in these accidents.
- Military personnel and students are the driver occupations most heavily involved in accidents on curves.
- Male drivers, in general, are almost 40% more involved in accidents on curves than are females and in particular experience higher frequencies of accidents on curves for all vehicle body types.
- The frequency of accidents on curves decreases with increasing driver age.
- Significantly fewer accidents occur on curves when seat belts are used.
- There is apparently a stronger dependence on vehicle body type than on driver age in accidents involving seat belt usage.
- Seat belt usage is apparently an indicator of driver prudence, in that vehicle types having the lowest frequencies of accidents on curves also have a low frequency of accidents on curves when seat belts are used, i.e., seat belt usage correlates with lower accident experience.

- There is a weak indication that the number of occupants in accident-involved vehicles is greater for older model years than for newer models.

- Drivers in the professional and clerical/sales occupations show a tendency toward having higher frequencies of accidents with later model year vehicles; this trend is reversed for skilled/semi-skilled workers and students.

- There are no clear trends in the ratio of accidents with male drivers relative to accidents with female drivers as a function of model year.

- Among the driver age brackets, only the 15-19-year age group experiences a higher frequency of accidents with older vehicles.

It should be kept in mind that the above findings are based on accident frequencies. For example, the first finding .... "Vehicles having the highest frequency of accidents on curves are the subcompact/mini and sporty models—..." could also be interpreted as "...subcompact/mini and sporty models have lower frequencies of accidents on straight sections of road." Thus, the frequencies indicated in this analysis represent the proportion of accidents of a particular type as experienced by a particular class of vehicle when compared to the total number of accidents of that class of vehicle. In the case of the first finding, the frequency for subcompact/mini vehicles would be computed as follows:

% Accident on Curves: Subcompact/Mini

$$= \frac{(\text{Number Accidents on Curves: Subcompact/Mini}) \times 100}{\text{Total Accidents Involving Subcompact/Mini Cars}}$$

A true accident rate, of course, would account for the total number of miles driven by subcompact/mini vehicles and would be reported in accidents on curves per mile of travel on curves. The mileage driven by individual vehicle makes is not available in King County, however, nor is the more refined statistic pertaining to miles driven on curves for individual vehicles. Without such exposure information, one is left to use accident frequencies (and not accident rates) as a means of establishing trends. The pitfalls in this procedure are real and a cautionary attitude in the interpretation of these findings is well advised.

5.1.2 Findings From the Texas Data. The accident data file from the State of Texas used in this study was derived from a 5% random sample of the vehicles involved in accidents during 1973, constituting approximately 39,000 vehicle involvements. As was the case in using the King County data, the Texas data were filtered so as to include only passenger cars, unimpaired drivers, and wet or dry road conditions. Unlike the King County data set, the Texas data set was limited to just single-vehicle accidents. As a consequence, the number of data elements in the Texas data set (2622 cases) is considerably less than was the case for the King County data set. The fewer data elements, clearly, restricted the level of complexity of the questions that could be addressed. For example, many questions that could be addressed in terms of specific make and model in the King County data set had to be restricted to the broader classification of body type for the Texas data set.

Specific findings obtained from the analysis of single-vehicle accidents drawn from the Texas 5% sample are:

- Small vehicles tend to have the highest frequencies of accidents on wet roads.
- Smaller vehicles tend to be over-involved in accidents on curved roads.
- In accidents involving loss of control, the sports cars and the large cars are under-involved, while the smaller vehicles are over-involved.

- There does not appear to be any correlation between body type and loss-of-control accidents on wet roads.
- There is a clear correlation between body type and overturning. The sports cars and larger vehicles are under-involved, while the smaller vehicles, especially the Volkswagen Bug, are over-involved.
- Vehicle size seems to have a direct correlation to hitting parked cars. The larger body types have the highest frequencies and the smaller body types the lowest frequencies.
- There is no obvious trend among accidents with just one occupant.
- Smaller vehicles are involved in more accidents in which a speeding violation is cited, while larger vehicles are less involved.
- Male drivers are over-involved in accidents with sporty vehicles.
- Younger drivers are over-involved in accidents on wet roads.
- There were about 2-1/2 times more males involved in accidents than females.
- For those drivers involved in accidents, the mean age of the male driver is 3.2 years younger than the female driver.
- The mean age of drivers involved in accidents ranges from about 19-27 for the smaller cars and 25-40 for the larger cars. Although some overlap exists between the two categories, it is clear that the average driver of a small car who is involved in an accident is several years younger than the average driver of a larger car involved in an accident.

- The mean age of drivers involved in accidents on curved roads is about three years less than the mean age of all drivers involved in accidents.

As with the King County data set, it should be kept in mind that these findings are based on an analysis of accident frequencies and not accident rates.

5.1.3 Comparisons. An examination of the specific findings cited in Subsections 5.1.1 and 5.1.2 show some agreement, some disagreement, and many findings which are not related. The latter situation results from the differences in the way the two accident data sets are coded. In areas where the codings are similar, however, some interesting comparisons can be made.

Table 5.1 consists of rankings of several kinds of accident descriptors for various vehicle body types. (See Appendix B for the body type classifications into which specific make/model classes fall.) Rankings are given for both the Texas and King County data with the lowest ranking numbers representing the greatest involvement with that kind of accident descriptor. For example, the subcompact/mini class had the highest frequency of accidents on curves in Texas. The body type categories are ordered, more or less, in increasing size from the top down with the exception of the lowest three body types. These latter three are considered to be in a separate specialty/pony category.

The first four columns on the left, i.e., Accidents on Curves, Accidents on Wet Roads, Overturning Accidents, and Accidents with One Occupant Only, are accident classifications that are associated with vehicle handling factors. The four columns on the right, i.e., Male Drivers, Drivers Between Ages 15-19, Mean Driver Age, and Mean Model Year, represent factors that are associated with various measures of vehicle exposure.

Table 5.1 A Comparison of Rankings from Studies of King County and Texas Accident Data.

Vehicle Body Type	Accidents on Curves			Accidents on Wet Roads			Overturning Accidents			One Occupant Only			Male Drivers			Drivers 15-19			Mean Driver Age			Mean Model Year		
	King Co.	Texas	Avg.	King Co.	Texas	Avg.	King Co.	Texas	Avg.	King Co.	Texas	Avg.	King Co.	Texas	Avg.	King Co.	Texas	Avg.	King Co.	Texas	Avg.	King Co.	Texas	Avg.
Sub-Compact/Mini	5	1	3	3	6	4.5	3	1	2	2	4	3	9	8	8.5	7	4	5.5	27.4	22.4	24.9	71.9	67.7	69.8
Sub-Compact	3	7	5	8	2	5	2	2	2	5	10	7.5	7	6	6.5	2	6	4	26.5	24.1	25.3	70.0	71.9	71.0
Compact	6	3	4.5	7	3	5	4	3	3.5	8	3	5.5	10	7	8.5	3	3	3	32.2	27.0	29.6	67.3	68.9	63.1
Intermediate	7	4	5.5	5	5	5	6	5	5.5	7	7	7	3	5	4	6	5	5.5	32.1	27.5	29.8	67.4	68.1	67.8
Standard/Full Size	8	6	7	6	7	6.5	7	6	6.5	9	6	7.5	6	9	7.5	5	7	6	34.8	31.8	33.3	66.2	66.7	66.5
Personal Luxury	9	10	9.5	4	8	6	9	9	9	1	8	4.5	8	3	5.5	10	8	9	37.3	34.7	36.0	66.8	68.3	67.6
Luxury Sedan	10	9	9.5	9	9	9	8	10	9	3	5	4	2	10	6	9	10	9.5	41.2	39.8	40.5	66.8	68.1	67.5
European Sports Car	1	5	3	1	1	1	1	7	4	6	1	3.5	5	2	3.5	4	1	2.5	24.6	19.1	21.9	67.0	66.1	66.6
Super Sport	2	8	5	10	10	10	10	8	9	10	2	6	1	1	1	8	9	8.5	29.0	24.5	26.8	67.7	68.9	68.3
Specialty/Pony	4	2	3	2	4	3	5	4	4.5	4	9	6.5	4	4	4	1	2	1.5	26.3	21.8	24.1	68.1	68.4	68.3

When the rankings for King County and Texas are averaged, there is a rough increase in accident frequencies with vehicle size for Accidents on Curves, Accidents on Wet Roads, and Overturning Accidents. Accidents with One Occupany Only seem to peak in the intermediate to standard size body types, although the pattern is weak. (The purpose of including Accidents with One Occupant Only is to explore the possible influences of vehicle loading on accident frequencies. Loaded vehicles, particularly in the rear, generally have less understeer and a lower static margin and hence may exhibit poorer handling qualities. Vehicles exhibiting higher frequencies of accidents with more than one occupant could, presumably, be experiencing load-related handling problems, namely, the vehicles exhibiting the lowest frequencies of accidents with one occupant only.) If there is any handling problem deriving from loading, it would be expected to appear with the smaller vehicles, since any load added to a smaller vehicle represents a greater proportion of the total weight of the vehicle. As is evident, however, no clear trend is apparent.

On examining the four exposure columns on the left of Table 5.1, the one that stands out is Mean Driver Age, in that there is a monotonic increase in driver age with increasing vehicle size. Another interesting feature in Table 5.1 pertains to the differences in mean age of the drivers in the King County accident data set as compared to the Texas data. The Texas data, it may be recalled, contains only single-vehicle accidents, while the King County data contains both single-vehicle accidents and the striking vehicle in accidents involving two, or more, vehicles. It is known, generally, that the mean age of drivers involved in single-vehicle accidents is lower than for accidents as a whole. Thus, the bias toward lower mean driver ages in the Texas data is to be expected. The differences, ranging between one and six years, seem high, however.

The highest percentages of male drivers involved in accidents are associated with the super sport vehicles. No clear pattern of male involvements is apparent in the other vehicle classes.

The preponderance of accidents involving drivers aged 15-19 years is concentrated among specialty/pony, European sports car and smaller class vehicles.

The Mean Model Year of vehicles in the subcompact and subcompact/mini classes is two to three years younger than the other classes. This finding results from the recent large increase of these smaller vehicles as a result of their wider manufacture in the United States in the years 1970-1973 and the growth in import car sales.

More specific comparisons of the King County and Texas data sets show some interesting results. Tables 5.2 and 5.3 show percent accidents on curved sections of road as a function of vehicle make and model for the King County and Texas data sets, respectively. Of the top six over-involved vehicles from the King County data, four are also over-involved in the Texas data. The only contradictory finding involves the Pinto—over-involved in accidents on curves in King County, but under-involved in Texas. Again, as a point of information, the percentages given were computed as follows, e.g., for the VW:

$$\text{\% VW Accidents on Curves} = \frac{(\text{Number of VW Accidents on Curves}) \times 100}{\text{Total Number of VW Accidents}}$$

The high percentage of smaller vehicles involved in accidents on curves suggests that vehicle handling may possibly be a factor here. It should be kept in mind, however, that, as per Table 5.1, smaller vehicles are usually driven by younger drivers, and younger drivers characteristically have higher accident frequencies than average. One is left, apparently, then, with the chicken-egg

Table 5.2. Seattle Single-Vehicle and Striking Vehicle Percent Accidents on Curved Sections of Road.

Vehicle Make/Model

Make/Model	% Involvement	(N)
Most Involved		
Opel Kadett, 1900, Ralye	25.0	(56)
VW Beetle	19.5	(41)
Toyota Corona, Crown	18.6	(97)
Pinto	18.2	(214)
Cougar	18.0	(89)
Dodge Coronet, Charger	17.9	(123)
Least Involved		
AMC Classic, Rebel, Matador	5.7	(88)
AMC Ambassador	7.0	(43)
Chrysler	7.1	(126)
Thunderbird, Landau	7.7	(104)
Cadillac Calais, DeVille, Brougham	7.7	(78)
Electra 225	9.1	(55)
Olds F-85, Cutlass, Vista-Cruiser	9.1	(153)
Total % Involvement	13.5	(9,523)

$$\% = \frac{(100)\text{ Accidents on Curves for a Given Make/Model}}{\text{Total Accidents for a Given Make/Model}}$$

Table 5.3. Texas Single-Vehicle Percent Accidents on Curved Sections of Road.

Vehicle Make/Model

Make/Model	% Involvement (N)
Most Involved	
VW Beetle	24.6 (118)
Opel Kadette, Other	21.1 (19)
Dodge Coronet, Charger	18.2 (66)
Camaro	16.7 (54)
Toyota Corona, Unknown	16.3 (43)
Least Involved	
Cadillac DeVille	0.0 (21)
Buick LeSabre, Wildcat	1.8 (55)
Thunderbird	4.0 (25)
Pinto	4.3 (46)
Ford LTD	5.7 (70)
Total % Involvement	11.4 (2,622)

$$\% = \frac{(100)\text{ Accidents on Curves for a Given Make/Model}}{\text{Total Accidents for a Given Make/Model}}$$

dilemma. In order to point up the situation, consider Table 5.4 which shows the mean driver age for the vehicles listed in Tables 5.2 and 5.3 as being most involved in accidents on curves.

Table 5.4. Driver Age Versus Make/Model Identified as "Most Involved" in Accidents on Curves.

Vehicle	Mean Driver Age King County (Seattle)	Texas
Opel Kadette	24.6	20.9
VW Beetle	26.6	22.5
Toyota	27.8	23.9
Pinto	28.4	25.2
Cougar	29.9	--
Dodge Coronet, Charger	29.3	26.1
Camaro	24.1	22.4

Similarly, consider the same information (Table 5.5) for the vehicles listed in Tables 5.2 and 5.3 as being least involved.

Table 5.5. Driver Age Versus Make/Model Identified as "Least Involved" in Accidents on Curves.

Vehicle	Mean Driver Age King County (Seattle)	Texas
AMC Classic, Rebel	34.9	--
AMC Ambassador	38.6	--
Chrysler	43.6	36.4
Thunderbird	35.1	33.2
Cadillac	44.3	43.0
Buick Electra	39.3	--
Olds F-85, Cutlass, etc.	35.0	27.4
Buick LeSabre	38.9	37.2
Ford LTD	--	33.0

The most striking comparison between Tables 5.4 and 5.5 is that the mean ages of drivers are all under 30 years for the most involved vehicles and, with the exception of one case, are all over 30 years for the least involved vehicles. The cause-effect relationship in vehicle handling accidents with respect to vehicle properties and driver skill/attitudes/experience is, therefore, not resolved.

As a final note, the finding that the Pinto is most involved in curve accidents in King County and least involved in Texas cannot be explained by age considerations. A difference in exposure to driving on curves may be a factor here, but this statement is only speculation.

A comparison of accidents on wet surfaces in King County and Texas is shown on Tables 5.6 and 5.7, respectively. The make/model comparisons between most involved and least involved vehicles on these tables do not compare nearly as well as do the data drawn from accidents on curves. One reason is due to the fact that the make/model classifications for the two sets of data do not match one-to-one. Another is that many make/model classes in the Texas data were not involved in enough accidents to produce any meaningful statistical information. Falling into this category are the AMC Ambassador, the Buick Riviera, and the Mercury Cougar which were most involved in wet surface accidents in King County, but were not among those evaluated in Texas due to too few accident cases. If these three vehicles are removed from the King County data set and the next three vehicles in order of percent involvement are added, then the listing of the most involved vehicles on Table 5.6 reduces to the following tabulation:

Make/Model	% Involvement	(N)
Valiant, Duster	42	(188)
Plymouth Belvedere, Satellite, GTX	41	(156)
Vega	41	(152)
Chevrolet Chevelle, Nomad, Greenbrier	40	(235)
Opel Kadette, 1900, Ralye	39	(56)

Table 5.6. Seattle Single-Vehicle and Striking Vehicle Percent Accidents on Wet Surfaces

Vehicle Make/Model

Make/Model	% Involvement (N)
Most Involved	
AMC Ambassador	47 (43)
Valiant, Duster	42 (188)
Plymouth Belvedere, Satellite, GTX	41 (156)
Vega	41 (152)
Riviera	40 (50)
Chevrolet Chevelle, Nomad, Greenbrier	40 (235)
Cougar	39 (89)
Least Involved	
Ford Capri	23 (61)
AMC Gremlin	25 (20)
Buick LeSabre, Wildcat, Centurion	26 (96)
Buick Electra 225	26 (55)
AMC American, Hornet	27 (67)
Mercury Monterey, Parklane, Marquis	27 (102)
Buick Special, Skylark, Sportwagon	28 (133)
Total % Involvement	36 (9,523)

$$\% = \frac{(100)\ \text{Accidents on Wet Surfaces for a Given Make/Model}}{\text{Total Accidents for a Given Make/Model}}$$

Table 5.7. Texas Single-Vehicle Percent Accidents on Wet Surfaces

Vehicle Make/Model

Make/Model	% Involvement	(N)
Most Involved		
Opel Kadette, Other	42.1	(19)
Buick Skylark, Special	38.2	(34)
Valiant, Duster	33.3	(54)
Pinto	32.6	(46)
Vega	32.3	(31)
Least Involved		
Dodge Dart, Swinger	13.9	(36)
Cadillac DeVille	14.3	(21)
Ford LTD	15.7	(70)
Thunderbird	16.0	(25)
Plymouth Belvedere, Satellite	17.6	(34)
Total % Involvement	21.9	(2,622)

$$\% = \frac{(100)\ \text{Accidents on Wet Surfaces for a Given Make/Model}}{\text{Total Accidents for a Given Make/Model}}$$

Each of these make/models has a counterpart in the Texas data and it can be noted that three of the top five most involved vehicles in King County also make up three of the top five most involved vehicles in Texas. It is evident, then, that there is a reasonable comparison among make/models for accidents on wet surfaces in the two sets of data. It should be noted that driving conditions in the two areas differ substantially. Whereas Texas can generally be classified as dry and flat, King County is just the opposite. This difference accounts for the larger percentage of wet surface accidents in King County. The similarity in findings obtained from such diverse driving environments is even more remarkable.

Overturning accidents are compared on Tables 5.8 and 5.9 for the two data sets. Four out of the top six vehicles most involved in overturning accidents in King County also make up four of the top five vehicles most involved in overturning accidents in Texas. Overturning accidents are the most recognizable accident type that can be associated with a vehicle design property. The overturning potential of a vehicle is, among other things, directly related to the ratio of its center-of-gravity height to track width. Since the height of the center of gravity is largely determined by ground clearance and the size of people, it does not vary greatly from vehicle to vehicle. Consequently, the major factor determining the overturning potential is track width. In the data shown on Tables 5.8 and 5.9, the vehicles showing the highest frequencies of rollover accidents are also the ones with the narrowest track widths. For example, prior to the 1974 models, the Toyota Corona had the narrowest track of any of the vehicles listed (51.2 in. track in front and 50.4 in. in the rear). By comparison, the VW Beetle has a front rack of 51.5 in. and a rear track of 53.1 in. The front and rear track of the Pontiac Firebird are 61.3 in. and 60.0 in., respectively. All vehicles in the "Most Involved" category have track widths of 57.5 in., or less, with the exception of the Plymouth Belvedere/Satellite model.

Table 5.8. Seattle Single-Vehicle and Striking Vehicle Percent Overturning Accidents

Vehicle Make/Model

Make/Model	% Involvement (N)
Most Involved	
Toyota Corona, Crown	8.4 (97)
Ford Capri	4.9 (61)
VW Beetle	4.9 (41)
Vega	3.9 (152)
Pinto	3.7 (214)
Valiant, Duster	3.4 (188)
Least Involved	
Ford Fairlane, Torino, Falcon	0 (274)
Oldsmobile F-85, Cutlass, Vista-Cruiser	0 (153)
Chrysler	0 (126)
Thunderbird, Landau	0 (104)
Cougar	0 (89)
Firebird	0 (60)
Total % Involvement	2.8 (9,523)

$$\% = \frac{\text{(100) Overturning Accidents for a Given Make/Model}}{\text{Total Accidents for a Given Make/Model}}$$

Table 5.9. Texas Single-Vehicle Percent Overturning Accidents

Vehicle Make/Model

Make/Model	% Involvement (N)
Most Involved	
VW Beetle	13.6 (118)
Toyota Corona, Unknown	7.0 (43)
Pinto	6.5 (46)
Plymouth Belvedere, Satellite	5.9 (34)
Valiant, Duster	5.6 (54)
Least Involved	
Chevrolet Chevelle	0.0 (130)
Pontiac Bonneville, Catalina	0.0 (67)
Oldsmobile 88	0.0 (58)
Buick LeSabre	0.0 (55)
Chevrolet Camaro	0.0 (50)
Chrysler	0.0 (50)
Total % Involvement	2.5 (2,622)

$$\% = \frac{\text{(100) Overturning Accidents for a Given Make/Model}}{\text{Total Accidents for a Given Make/Model}}$$

All vehicles in the "Least Involved" category have track widths of 58.5 in., or over, with some as high as 63.5 in. The data show the importance of track width in reducing overturning potential, although again, as shown in Table 5.3, the majority of the most involved vehicles are also driven by younger drivers.

Accidents on curves, on wet surfaces, and overturning accidents represent three accident categories where vehicle handling problems may become evident. Other accident descriptors such as loss of control, skidding, rear-end collision, sideswipe, wet-curve involvements, number of vehicle occupants, driver occupation, driver age and sex, and many others may provide information concerning the influence of vehicle handling on accident causation. These factors, and others, as could be investigated with the King County and Texas data are discussed in Appendix B.

5.2 The CPIR Data File

The CPIR Accident Data File consists of accident data which is recorded on the General Motors Collision Performance and Injury Report Long Form. The file consists of cases reported by Multi-Disciplinary Accident Investigation (MDAI) teams under the sponsorship of the National Highway Traffic Safety Administration, the Motor Vehicle Manufacturers Association, and the Canadian Department of Transportation. As of March 1975, there were 7,799 case vehicles coded in the file.

The purpose in examining the file was to determine whether there was any information which could be immediately utilized in shedding some light on the role of vehicle handling in accident causation. It was anticipated that subsequent work would involve developing indepth accident data collection methods which would be oriented toward the identification of vehicle handling factors in accidents. These methods would then be used to collect a set of accident cases—specifically investigated for vehicle handling factors—which should be used as a data set for statistical analysis. Ultimately this data set would be used to determine the role of vehicle handling in accident causation in statistical terms. As a first step, however, it was of interest to determine what could be done with the data already in the CPIR file.

In making this assessment, it appeared advisable to filter out passenger car accidents wherein only unimpaired drivers were involved. (See the discussion in Section 3 regarding the rationale for restricting vehicle handling accidents to those involving unimpaired drivers.) A vehicle handling accident, at this juncture, was determined to be one where the driver attempted to execute an avoidance maneuver prior to the collision events. Using this filtering rationale, some 722 CPIR accidents were identified where the driver attempted to brake (348), steer (91), brake and steer (268), accelerate (11), or accelerate and steer (4). A sample of twenty-four of these 722 cases were then carefully reviewed for purposes of determining whether vehicle handling factors were a causative mechanism in the accident [34]. Ten of the cases involved braking maneuvers only, ten involved steering maneuvers only, and the remaining four involved braking and steering. The twenty-four cases are identified in Table 5.10.

In this review, vehicle handling was considered to be a causative factor if a better performing vehicle or a more determined driver action could have avoided the accident (see Section 3.2). In order to decide whether vehicle handling was a factor, enough information had to be available in a given report to reasonably reconstruct the vehicle paths and associated driver control actions. Seventeen of the cases had this degree of information, although none were informative enough to pin-point the sequence of driver perception, decision making, and control action.

In all seventeen of these cases, it could reasonably be concluded that the driver of the case vehicle was a causative factor in the accident. In no case could it be definitely concluded that a better performing vehicle (e.g., shorter braking distance,

Table 5.10. CPIR Cases Reviewed for Vehicle Handling Factors

Case	Description
	A. Vehicle Handling: Accidents Involving Only Braking Maneuvers
1. AA-144	Car-to-Car Rear-End Impact/Unlicensed Driver[1]
2. AA-324	Passenger Car/Pedestrian[1]
3. AA-105	Car/Car/Rear-Impact[1]
4. 4-ME-13	Auto/Auto/Front-End/Rear-End[2]
5. MVD-10	Auto/Auto-Rear-End[2]
6. AA-197	Motorcycle/Car Head-On[1]
7. 201	Pedestrian/Car Collision[1]
8. AA-195	Car/Pedestrian Collision[1]
9. B.U.71-14	Car/Car Angle Collision[3]
10. 4-ME-20	First Impact - Auto/Truck/Auto[2] Second Impact - Auto/Auto/Freeway
	B. Vehicle Handling: Accidents Involving Only Steering Maneuvers
1. 71-36B	Three Vehicles: Front to Side, Side to Side[5]
2. 025-71	Car/Parked Cars/Collision[4]
3. 71-3	Car/Car - Intersection[6]
4. 64	Car/Car Front-to-Rear Collision[5]
5. 36	Fixed Object Impact[5]
6. 4-ME-37	Auto/Truck - Head-On[2]
7. 4-ME-26	Auto/Auto - Left Front/Left Front[2]
8. AA-344	Single Vehicle/Loss of Control[1]
9. AA-140	Two Car/Head-On Collision[1]
10. AA-302	Passenger Car/Right-Angle Intersection Collision with Passenger Car[1]

Table 5.10 (Cont.)

Case	C. Vehicle Handling: Accidents Involving Braking and Steering Maneuvers
1. UNM 66	Two Vehicle Intersection Collision[7]
2. MI-325	Car/Car Head-On[8]
3. HSRI-454	Car/Loss of Control[1]
4. OK-333	Car/Loss of Control[1]

Authors

[1]Highway Safety Research Institute

[2]Bayor College of Medicine

[3]Boston University

[4]Accident and Defect Investigation Division, Ottawa, Canada

[5]Cornell Aeronautical Laboratory

[6]University of Southern California

[7]University of New Mexico

[8]University of Miami

or shorter turning radius) would have prevented the accident. There were, however, six cases where vehicle performance may have been a contributing factor which precipitated the accident. These included loss of control events in cases A-197, 025-71, 36, AA-344, HSRI-454, and OK-333. The separate contributions of the driver and vehicle (as well as perhaps the roadway) could not be reasonably determined with the information available, however.

It is evident that the CPIR accident file, as presently constituted, is not suited for making decisions in a deterministic manner regarding the presence, or lack thereof, of vehicle handling factors in case accidents. A more specific scheme for gathering information will be required which is specifically oriented toward reconstructing the pre-crash phase of the accident—the phase in which vehicle handling factors are most important. Such a scheme is presented and discussed in Section 7 and Appendix D of this report. Even with the aid of the proposed scheme, the pin-pointing of events involving driver perception, decision making, control actions, etc., will be most difficult. At least as difficult will be the task of assessing the interaction between the driver, the vehicle, and the road surface in arriving at final decisions with respect to the causative factors.

If, on the other hand, the CPIR data is contemplated for use as a data base for making statistical inferences regarding the role of vehicle handling in accident causation, then other difficulties will arise. These difficulties are discussed (more appropriately) in Section 7.

BLANK

6.0 SELECTION OF VEHICLE HANDLING PERFORMANCE DESCRIPTORS AND CONSTRUCTION OF A VEHICLE HANDLING DATA FILE

In determining the role of vehicle handling in accident causation, it is necessary to break down the elements of a passenger car into those qualities, quantities, descriptors, dimensions, etc., that describe its handling performance. Next it is necessary to do the same with the accident event, i.e., break down the event into its elemental descriptors, each of which may have a connection with the vehicle handling properties of the driver/vehicle/road-surface system. Having performed these tasks, one must proceed to (1) collect the necessary vehicle and accident data and (2) construct the related computerized data files. The final step is that of computing normalized accident rates and analysing the resultant data for correlations between vehicle descriptors, accident descriptors, and accident rates. This latter task is exceedingly complex and the next section of this report (Section 7) discusses this crucial aspect of the overall methodology.

The process of defining and selecting vehicle handling descriptors is discussed below. Following consideration of each of the steps employed in this task, decisions are made as to the form and content of a vehicle handling data file as governed by practical considerations and available data.

6.1 Selection of Vehicle Handling Performance Descriptors

The method used to formulate a set of passenger car properties sufficient to describe its handling performance involved the following five steps:

1. identify vehicle characteristics governing driver behavior and risk perception
2. identify vehicle characteristics governing driver-vehicle performance in accident avoidance maneuvers

3. identify the descriptors defining the initial conditions and control failures leading to an accident event

4. formulate hypotheses linking accident descriptors to vehicle performance descriptors

5. define needed accident data and vehicle performance data

Each of these steps is defined in the following subsections.

6.1.1 Vehicle Characteristics Governing Driver Behavior and Risk Perception. The objective here is to identify all aspects of driver-vehicle control and vehicle response characteristics that could conceivably influence a driver's perception of the degree to which he is driving in a prudent (i.e., "safe") manner. In identifying these characteristics, it is reasonable to consider the manner in which a driver perceives risks and establishes his driving norm. It is further reasonable to identify those characteristics that influence the driver's perception of the controllability and stability of his vehicle. To the degree that a driver gains the impression that his vehicle is highly controllable and is insensitive to external disturbances, it can be assumed that a driver perceives his vehicle to be "roadworthy."

Nine characteristics have been postulated as probable influences of the driver's perception of the roadworthiness of his vehicle:

(1) acceleration produced in response to throttle over the range of operating speeds

(2) ability of the driver to modulate the thrust of the drive wheels so as to prevent wheel spin

(3) ability of the driver to modulate his braking input so as to achieve a desired deceleration and prevent lockup of either the front or rear wheels

(4) lack of a directional response to a braking input

(5) ability of driver to perceive tire-road traction levels as influenced by road conditions

(6) change in the static and dynamic response to steering over the range of operating speeds

(7) amount of and change in the directional response resulting from road camber and cross-winds over the range of operating speeds

(8) degree to which a braking/turning maneuver is affected by road roughness causing a jounce/rebound response of the running gear

(9) level of operator comfort as influenced by seating, ride motions, noise, vibration, etc., over the range of operating speeds.

Given that the above nine characteristics or qualities constitute the performance factors that influence the driver's conscious or subconscious attitude towards the roadworthiness of his vehicle, methods are then required for defining these qualities in objective terms. By and large, however, the premise that driver perception of roadworthiness influences the process by which drivers make judgments relative to the prudency of their driving behavior is largely unexplored. Consequently, to a large extent, logic and intuitive reasoning must be used to develop the required objective measures. The required list, developed on this intuitive basis, follows in Table 6.1.

6.1.2 Vehicle Characteristics Governing Driver-Vehicle Performance in Accident Avoidance Maneuvers. Vehicle characteristics governing driver-vehicle performance in accident-avoidance maneuvers are not necessarily those which can be or are perceived by a driver in his assessment of vehicle roadworthiness. Although there are no data to indicate that this hypothesis is valid, it

Table 6.1. Performance Measures and/or Design Parameters Serving to Quantify Driver Perception of Vehicle Roadworthiness

Quality	Measure or Parameter
(1) acceleration produced in response to throttle over the range of operating speeds	(a) transient response of engine to step throttle displacement at specified road-loading conditions
	(b) velocity vs. time performance data
	(c) maximum speed on level grade
	(d) integral of thrust available minus level road-load thrust
	(e) ratio of engine horsepower to weight of vehicle
(2) ability of driver to modulate the thrust of the drive wheels so as to prevent wheel spin	(a) accelerator-pedal displacement per unit displacement of the throttle valve
	(b) tightness of throttle control and level of friction in the throttle-control system
	(c) response time of the engine-driveline system
	(d) accelerator pedal force per unit displacement of the pedal
(3) ability of the driver to modulate his braking input	(a) pedal-force/deceleration gain
(4) lack of a directional response to a braking input	(a) magnitude of king-pin offset
(5) ability of driver to perceive tire-road traction levels	(a) magnitude of dry friction in the steering system
	(b) presence/lack of power-steering system
	(c) radius of gyration in yaw ratioed to the wheelbase

Table 6.1 (Cont.)

Quality	Measure or Parameter
(6) change in static and dynamic response to steering over the range of operating speeds	(a) understeer level and change in understeer with vehicle payload
	(b) total cornering coefficient of the installed tires and its variation with payload
	(c) body roll per unit lateral acceleration
	(d) level of roll damping
	(e) ratio of c.g. height to track width
	(f) radius of gyration in yaw ratioed to the wheelbase
(7) amount and change of directional response resulting from road camber and crosswinds	(a) understeer level and change in understeer with vehicle payload
	(b) roll compliance-roll steer product

can be conceived that there are vehicles that cause a driver to behave in a very cautious or overly prudent manner even though the emergency maneuvering capability of the vehicle is reasonably high. Consequently, it becomes necessary to identify those characteristics or qualities that are presumably relevant to accident avoidance, per se, rather than to the driver's impression of the degree to which he can exercise control.

Ten general categories of performance characteristics, postulated to influence or constrain the ability of a driver-vehicle system to avoid an accident, are listed below. An understanding of the mechanics of tire-vehicle systems, as currently exists, is employed to (1) identify specific open-loop measures of vehicle performance, (2) specify mechanical properties of the system, and (3) specify design parameters that are either known to influence driver-vehicle performance or can be postulated as a likely determinant of driver-vehicle performance in accident-avoidance maneuvers. These measures/properties/parameters are tabulated in Table 6.2 to the right of the emergency maneuvering characteristics with which they are associated. The symbols and notations used are taken from Reference 35 and are defined at the end of Table 6.2.

6.1.3 Accident Event Descriptors. It appears reasonable to break down an accident event such that four categories of descriptors can be used to identify the characteristics of the event. The postulated categories are:

1. The "initial conditions" describing the driver/vehicle/road-surface system prior to the accident event.
2. The circumstances precipitating the accident.
3. The contributing judgments, decisions and actions of the driver.
4. The path of the vehicle(s).

Table 6.3 constitutes a delineation of each of these descriptor categories.

Table 6.2. Emergency Maneuver Performance Measures

Characteristic/Quality	Measure/Parameter
(1) lateral or curvilinear motion capability on dry road surfaces	(a) limit response to trapezoidal steer input of $\sigma'=24$, as measured by the response numeric $R_s(1/R)_{ave}$ [35]
	(b) limit steady-state lateral acceleration in a constant-velocity turn (i.e., in a standard skid-pad test)
	(c) product of the ratio of track width to c.g. height and peak value of $F_y/F_z)_{tire}$, as measured at F_z = Car Weight/4
(2) qualities inhibiting or promoting driver ability to utilize the max. curvilinear capability in a controllable manner	(a) early saturation of cornering capability as measured by value of $\sigma'_{saturated}/24$ [35]
	(b) $\partial R_s(1/R)_{ave}/\partial\sigma'$
	(c) magnitude of peak side-slip response at $\sigma'=24$ [35]
	(d) nonlinear increase in peak sideslip rate as $R_s(1/R)_{ave}$ increases as measured by $\sigma'_{break}/24$, where σ'_{break} is the value of normalized steer angle at which the departure from quasilinear behavior occurs [35]
	(e) magnitude of δ_{sw} when $\sigma' = \sigma'$ at which $R_s(1/R)_{ave}$ first reaches a maximum ($\delta_{sw} = N_g \frac{\ell}{10} \sigma'$) [35]

Table 6.2 (Cont.)

Characteristic/Quality	Measure/Parameter
	(f) time delay between initiation of trapezoidal steer input and peak value of yawing velocity response [35]
	(g) damping ratio of the roll oscillations of the sprung mass
	(h) damping in yaw as defined by the ratio r_p to r_{min} (following r_p) as a function of σ' [35]
(3) straight-line deceleration capability without loss of steering control and directional stability (on dry surfaces)	(a) limit wheels-unlocked deceleration capability
(4) straight-line deceleration capability without loss of steering control and directional stability (on wet road surfaces)	(a) classical measure of braking efficiency on a wet road
	(b) ratio of gross net area of tire footprint
	(c) product of (a) and (b)
(5) qualities inhibiting or promoting driver ability to utilize maximum stopping ability	(a) order of wheel lockup on dry road surface
	(b) order of wheel lockup on a wet road surface
	(c) deceleration/pedal-force gain
	(d) pedal force capability of the 50 percentile female driver minus the pedal force required to lock the wheels on a dry road surface

Table 6.2. (Cont.)

Characteristic/Quality	Measure/Parameter
	(e) damping ratio of the pitch oscillations of the sprung mass
(6) capability to execute a fast lane change with a symmetric (bipolar) steering input	(a) product of $\Delta\psi$ and Δ produced at 3.4 sec. following a 2-sec. sine wave of steering with $\sigma{=}\sigma)_{\Delta min}$ (evaluate this product for steer right first and steer left first at V=45 and 60 mph) average results for both speeds to yield a separate numeric for steer right first and steer left first [35]
	(b) above numerics averaged for right and left lane changes
	(c) numerics in (a) subtracted to yield a measure of asymmetry in behavior
(7) qualities which make a vehicle forgiving to steering errors in a fast lane change	(a) response to a 2-sec. sine wave of steering as quantified by the integral $\oint_2^{18} \Phi d\sigma$ where Φ = radius vector from original to the β_p vs. Δ curve and σ is the variable along the curve (evaluated separately for V=45 mph and 60 mph) [35]
	(b) mean of the above numeric as evaluated for the two speeds
	(c) response to a 2-sec. sine wave of steering as quantified by $\sum_{\sigma=2}^{18} \beta_p(\sigma) \times \Delta(\sigma)$

Table 6.2. (Cont.)

Characteristic/Quality	Measure/Parameter
	(evaluated separately for 45 and 60 mph) [35]
	(d) mean of the numerics in (c) as evaluated for the two speeds.
(8) resistance to rollover in maneuvers causing large side forces to be created at tire-road contact	(a) product of $\phi_p\big\vert_{max} \times \frac{1}{N} \sum_{i=1}^{N} \phi_p\big\vert_i$ where $\phi_p\big\vert_{max}$ is the maximum value of ϕ_p obtained in the total series of N test runs and $\frac{1}{N} \sum_{i=1}^{N} \phi_p\big\vert_i$ is the average of the value of ϕ_p attained in N test runs [35]
	(b) ratio of height of c.g. above ground to the average track width
	(c) ratio of height of car to average track width multiplied by a constant that reflects the ratio of c.g. height to total height
(9) deceleration capability in a turn before encountering loss of steering control or directional instability due to lockup of front or rear wheels, respectively	(a) maximum value of $A_x\big\vert_{ave}$ achieved prior to wheel lock in a right turn and in a left turn [35]
	(b) mean of the two numerics defined in (a)

Table 6.2 (Cont.)

Characteristic/Quality	Measure/Parameter
(10) qualities inhibiting or promoting driver ability to stay in a curve during braking	(a) product of $\frac{1}{R_0(1/R)\big\|_{peak}} \times \bar{A}_x\big\|_{ave}$ where $R_0(1/R)\big\|_{peak}$ is the minimum value of the average path curvature ratio as a function of $A_x\big\|_{ave}$ and $\bar{A}_x\big\|_{ave}$ isthe value of $A_x\big\|_{ave}$ at which the maximum value of $R_0(1/R)$ is obtained [35]
(11) ability of vehicle to "hold the road" in the presence of road roughness	(a) mean value of $R_0(1/R)$ averaged over all runs for all three roughness frequencies [35]

SYMBOL INDEX

Symbol	Definition
A_x	Longitudinal acceleration of vehicle
F_y	Lateral force on vehicle
F_z	Vertical force on vehicle tires
ℓ	Wheelbase
N_g	Steering gear ratio
r	Yaw rate
R	Instantaneous radius of curvature
R_0	Initial radius of curvature
R_s	Radius of curvature for a steady 1 g turn at 40 mph
β	Vehicle sideslip angle

Symbol	Definition
δ_{sw}	Steering wheel amplitude for sine steer tests $= \frac{66}{V} \frac{\ell}{10} \sigma \dot{N}_g$; σ = 2, 4, 6, 8, 12, 16
Δ	Lane change deviation in sinusoidal steer tests (see Reference 35 for a more complete definition)
σ'	Normalized steer angle in trapezoidal steer tests
ϕ	Roll angle
ψ	Heading angle

Table 6.3. Accident Event Descriptors

I. The Initial Conditions

1. Vehicle descriptors

(a) make, model, and model year

(b) engine size

(c) type of transmission

(d) power boosts on controls, if any

(e) make, size, and model of installed tires

2. Vehicle operational-status descriptors

(a) mechanical condition of steering and suspension components

(b) modifications, if any, to steering and suspension components

(c) passenger/payload weights and distribution, including fill status of the fuel tank

(d) cold inflation pressures of intact tires

(e) speed of vehicle prior to control action or maneuver decision

(f) location of vehicle with respect to leading and following elements in the traffic stream

3. Tire-road interface descriptors

(a) presence/absence of interfacial contaminant

(b) measure of frictional quality of roadway under the prevailing contaminant condition

(c) depth of tread on each tire

(d) presence and amount (i.e., magnitude) of road profile having a frequency content that would excite a significant response (jounce/rebound) of the tire-wheel system leading to effective reductions in tire-road contact

4. Roadway descriptors

   (a) roadway geometry (tangent, curve, grade, entry/exit ramp, intersection) requiring a maneuver independent of the maneuver(s) associated with the accident

   (b) posted speed at location where accident occurred

   (c) 85th percentile speed of traffic at location where accident occurred

   (d) external distractions (scenery, pedestrians, etc.)

   (e) general visibility of roadway, traffic, and obstacles as influenced by time of day, weather, and lighting provided by vehicle and luminaires

   (f) intensity (amount) and nature of the traffic requiring surveillance by driver

5. Trip objectives

   (a) trip purpose (degree of urgency, degree of routineness)

   (b) level of responsibility felt by driver for safety of passengers

   (c) travel-time pressures, if any

6. Driver descriptors

   (a) age and sex

   (b) weight and height

   (c) years of driving experience

7. Driver status (condition)

   (a) familiarity with vehicle

   (b) familiarity with route

   (c) psycho-motor impairments, if any

   (d) driver-vehicle fit from the ergonomic point of view

II. The Precipitating Event (A Vehicle/Roadway/Traffic/Obstacle Relationship Requiring Driver Action in Excess of Normal Guidance)

1. Vehicle-roadway conflicts

   (a) sudden emergence of roadway curvature into driver's line of sight

   (b) misinterpretation of signing requiring a sudden route correction

   (c) appearance of pavement irregularity which would cause problems if traversed at speed

   (d) sudden change in tire-road surface friction couple (e.g., ice on bridge)

   (e) unexpected change in lane geometry

   (f) change in traffic signal, placing driver in a compromised position

   (g) realization or recognition that vehicle is moving along an undesired trajectory

   (h) location of vehicle along roadway at instant the above conflicts were perceived

2. Vehicle-traffic conflicts

   (a) sidewise encroachment of another vehicle in the lane of travel

   (b) sudden deceleration of a preceding vehicle

   (c) turning traffic at an intersection

   (d) presence of vehicles desiring to cross or enter the traveled lane

   (e) location of vehicle with respect to the traffic elements at the instant the above conflicts were perceived

3. Vehicle-obstacle conflicts

   (a) sudden emergence of an obstacle in the desired lane of travel

(b) diversion of driver's attention leading to a compromised relationship with obstacles and traffic if and when attention is restored

(c) lack of attention to caution signs leading to high speed encroachment of traffic barriers

(d) location of vehicle in relationship to obstacles at the instant the driver perceived the above conflicts

III. Driver Judgment, Decisions, and Control Actions

1. Evidence that driver misjudged speed and distance relative to the conflict to be resolved

2. Evidence that driver misjudged the control margin established by the initial conditions

3. Distance and time utilized by driver in deciding on his control actions

4. The location of the vehicle at the instant that control actions were instituted to resolve a conflict or maintain vehicle stability and control

5. Driver's objective, viz., to:

   (a) slow down

   (b) stop

   (c) change lane or leave roadway

   (d) avoid obstacle by steering

   (e) avoid obstacle by steering and braking

   (f) speed up to avoid being struck by a moving vehicle

6. Evidence of control action satisfying these objectives:

   (a) nature of control action

   (b) amount of control action

IV. Vehicle Trajectory

1. Location of impact
2. Speed at impact
3. Location at which vehicle left roadway or overturned
4. Estimate of the braking and turning accelerations required to produce the observed trajectory
5. Degree to which the vehicle sideslipped or spun
6. Degree to which the vehicle did not recover from the initial maneuver
7. Final resting place of vehicle relative to the struck obstacle, the roadway, and the point of impact

6.1.4 Hypothesis Formulations. The hypotheses presented here are divided into two classes:

1. those relating vehicle performance to driver risk taking, and

2. those relating vehicle performance to accident avoidance.

Each set of hypotheses is formulated on the basis of a one-to-one relationship between dependent and independent variables. Obviously, hypotheses which link two or more vehicle qualities acting in concert to increase/decrease the involvement rate in a significant manner can also be developed. Note also that the hypotheses speak only to qualitative descriptors in terms of vehicle performance and the accident event. Clearly, the hypotheses could be cast in an objective format by substituting specific objective quantities for the associated qualitative descriptor. This substitution has, in fact, been done. In later sections of the report, specific accident, vehicle, and road-surface descriptors are specified to define the required data sets (Sections 6.2, 7, and 8) and to determine a vehicle handling supplement for the CPIR accident report form (Section 8). The hypotheses presented in Tables 6.4 and 6.5 constitute, in effect, a means for crystalizing one's thoughts and for subsequently developing these more specific outputs.

Table 6.4. Hypotheses Relating Vehicle Performance Measures to Driver Risk Margins

1. High level of acceleration/throttle gain (and quick responsiveness of drive thrust to application of throttle) leads to driver willingness to accept narrower gaps in merging with and crossing against a stream of traffic.

2. Low levels of acceleration/throttle gain and sluggish response of drive thrust to throttle leads to unconservative application of the throttle in acceleration maneuvers.

Table 6.4 (Cont.)

3. Low levels of acceleration/throttle gain and sluggish response to throttle leads to the maintenance of headways that are lower (smaller) than would be deemed prudent by the average driver-vehicle combination in comparable circumstances.

4. Easy modulation of the throttle, i.e., a capability of precisely controlling drive thrust, in combination with an ability to precisely modulate braking, leads to lower (smaller) headways being maintained than would be true if the opposite performance qualities existed.

5. A capability for precisely controlling drive thrust leads to driver willingness to execute traction-demanding maneuvers on reduced-friction surfaces that are higher than what would normally be the case.

6. Platoon avoidance behavior is not related to the acceleration and braking properties of a vehicle other than it is more probable that vehicles which provide more comfort to the driver at high operating speeds will tend to avoid platoons by operating at velocities in excess of platoon speeds.

7. Pedal-force/deceleration gains providing greater precision in modulating the brake will lead to drivers accepting smaller headways in a traffic stream.

8. Pedal-force/deceleration gains providing greater precision in modulating the brake will lead to drivers making less conservative application of the brake in a deceleration maneuver. (Less conservative means he will brake more energetically or that he will delay longer before applying the brake.)

9. Vehicles that exhibit minimal directional response during braking make drivers more comfortable and more likely to operate at high speeds and, conversely, vehicles that exhibit a large sensitivity to brake imbalance will be driven more conservatively with respect to speed selection.

Table 6.4 (Cont.)

10. Vehicles designed to give the driver a high degree of awareness of the traction levels prevailing at the tire-road interface will be driven more conservatively (speeds and headways) on reduced traction surfaces.

11. Vehicles that exhibit less change in their static and dynamic response to steering as speeds and payloads are varied will be driven at speeds that are higher than that speed which would be deemed prudent by an average driver in a vehicle whose directional behavior is more sensitive to speed and payload.

12. Vehicles that are less sensitive to external disturbances than the average vehicle will be driven at speeds that are higher than the speeds at which the average prudent driver will drive an average vehicle.

13. Vehicles that are less sensitive to changes in road crown are likely to be driven at higher speeds on crowned rural roads with a greater likelihood of avoiding platoons by means of continual passing maneuvers.

14. Vehicles that exhibit a high level of wheel control (i.e., damping of the wheel hop mode) in the presence of road roughness will, on the average, be maneuvered more aggressively on rough pavements than is the case for vehicles whose maneuvering performance is more substantially degraded by road roughness.

15. Vehicles that exhibit a high level of wheel control, in combination with (1) an insensitivity to quasi-static external disturbances, (2) good braking modulation, and (3) good road feel are more likely to be driven under weather conditions and circumstances in which an average prudent driver, in an average vehicle, would elect not to make the trip.

16. Vehicles that provide a high level of operating comfort are more likely to be operated at higher speeds for longer durations of time.

Table 6.5. Hypotheses Relating Vehicle Performance Qualities to Driver Success/Failure in Avoiding an Accident

1. Drivers with minimal driving experience (i.e., number of emergencies), on being exposed to an emergency occurring during good weather, are likely to make maneuver demands that are less than the inherent maneuvering capability of the vehicle.

2. Conversely, such drivers are likely, during reduced tire-road friction conditions, to make maneuver demands that are greater than the maneuvering potential possessed by the vehicle.

3. Vehicles possessing large steady-state curvilinear motion capability on a dry surface are not likely to be more successful in avoiding obstacles (i.e., be less involved in accidents) than are vehicles with lesser curvilinear motion capability.

4. Vehicles that respond more quickly to steering control (without significant overshoot in their response) are likely to be less involved in accidents where the primary maneuver requirement is one of displacing the vehicle to the right or left as quickly as possible.

5. A vehicle that exhibits a large sideslip angle as it attains a large path curvature is more likely to become uncontrollable by an average driver and consequently be more involved in accidents that require emergency turning to avoid a collision.

6. Emergency braking in urban traffic scenarios is likely to result in panic stops with all wheels locked such that locked-wheel tire-traction levels are the primary determinant of collision avoidance potential.

7. The success of emergency braking maneuvers in operational scenarios involving high traffic speeds and various external disturbances depends primarily on the level of deceleration that can be achieved without locking front or rear wheels. Consequently, vehicles with well balanced braking systems and effective tires should be less productive of accidents involving braking at high speeds provided drivers are not operating such vehicles with less margin for error.

Table 6.5 (Cont.)

8. A higher probability of wheel lockup exists for braking on wet (reduced friction) surfaces leading to the hypothesis that vehicles having pedal force/ deceleration gains providing for good modulation are less likely to become involved in braking-related accidents on wet roads.

9. Vehicles with high pedal force/deceleration gains should be over-involved in dry-road braking accidents when driven by small females that possess less than average maximum pedal-force capabilities.

10. Vehicles that possess response characteristics such that a symmetric steering input of short duration produces a substantive lateral displacement with minimal heading change are more likely to be under-involved in accidents in which the required obstacle avoidance maneuver must be constrained so as to keep the vehicle on the roadway.

11. Vehicles exhibiting a response to a symmetric steering input of short duration in which the magnitude of lateral displacement is not overly sensitive to driver error (i.e., choosing the correct steer amplitude) are more forgiving and consequently are likely to be less involved in accidents resulting from unsuccessful lane change maneuvers.

12. Vehicles with design characteristics that minimize their rollover potential from both a static and a dynamic viewpoint are less likely to be involved in rollover accidents accompanying the execution of a drastic maneuver or following those maneuvers in which the vehicle departs from the paved roadbed.

13. Vehicles capable of achieving in turns a wheels-unlocked longitudinal deceleration level only minimally reduced from the values attainable in straight-line braking should be less productive of loss-of-control incidents accompanying braking on curved roadway sections.

Table 6.5 (Cont.)

14. Vehicles in which rear wheels lock up prior to front wheels are likely to be more involved in braking-related accidents than vehicles in which the front wheels lock first. This differentiation should be more pronounced for accidents in which drivers are required to brake during a turn.

15. Vehicles in which the vertical motion of the wheel masses is highly controlled by the selected level of shock absorber damping are likely to be less involved in accidents occurring on rough road surfaces than on smooth road surfaces.

6.2 Vehicle Performance Parameters and Indices

On the basis of the reasoning, arguments, and hypotheses presented above, vehicle performance descriptors have been identified which, on being correlated with the accident record, would speak to the role of vehicle handling in accident causation. Unfortunately, data on vehicle performance, as defined by the descriptors presented earlier, is not generally available. In certain cases, the data do not exist for all makes and models in the vehicle population and in other cases, the data may exist but are not generally available to the highway safety researcher. Accordingly, it is necessary to distinguish between performance descriptors that constitute an ideal fulfillment of the requirements established by the hypotheses posed earlier and descriptors that can be obtained from currently available sources. A pragmatic resolution of this problem results in the establishment of a "non-ideal" set of descriptors which can be divided into:

- design parameters
- handling performance indices
- limit handling performance indices

6.2.1 Design Parameters. Design parameters are those quantities or specifications which describe a vehicle in terms of weight, dimensions, load distributions, etc. The handling-related design parameters listed in Table 6.6 can be obtained from the passenger car specifications [36] published by the Motor Vehicle Manufacturers Association, as derived from data supplied by the domestic manufacturers of motor cars.

6.2.2 Normal Handling Performance Indices. Normal handling performance indices (see Table 6.7) are defined here as quantities which describe vehicle performance under ordinary driving conditions. The first thirteen of the indices listed in Table 6.7 were derived from the Design Parameters tabulated in Table 6.6. Thus these performance indices can be determined for all American passenger cars. The next seven indices can be derived from test data produced in steady turns and in transient responses to a "step" displacement of the steering wheel. The final six indices can be collected from information published in popular motoring magazines such as Motor Trend, Road and Track, etc.

6.2.3 Limit Handling Performance Indices. Limit handling performance indices are properties which describe the performance of a vehicle at the limits of its controllability. Nineteen indices were derived from the Vehicle Handling Performance [35] numerics developed earlier for the National Highway Traffic Safety Administration. These indices are given in Table 6.8, as derived from the ideas expressed in Table 6.2 and limited to those situations in which applicable data can be obtained.

Table 6.6. Design Parameters

Parameter Name	Symbol
Wheelbase	ℓ
Length	L
Average Track	T
Height	H
Ground Clearance	h
Manufacturer's Spec. Front Tire Pressure	P_F
Manufacturer's Spec. Rear Tire Pressure	P_R
Front Brake Effectiveness, %	Γ
Manual Brake Line Pressure at 100 lb Pedal Load	P_{100}
Power Brake Line Pressure at 100 lb Pedal Load	P'_{100}
Manual Steering Overall Gear Ratio	G_M
Power Steering Overall Gear Ratio	G_P
Area of Side Window Glass	A
Curb Weight	W
Curb Weight on Front Axle	W_F
% Load on Front Axle for Front Seat Passengers	%FF
% Load on Front Axle for Rear Seat Passengers	%FR

Table 6.7. Normal Handling Performance Indices

Index Name	Symbol
Yaw Moment of Inertia (From I_z=1.26 W-1750, see Ref. 37)	I_z
Non-dimensional I_z	$\dfrac{I_z}{(\frac{W}{32.2})\ell^2}$
Weight Distribution	W_F/W
Brake Torque Imbalance	$\dfrac{\Gamma}{W_F/W \times 100}$
Zero Speed Path Curvature Gain	$\dfrac{10^5}{G\ell}$
Roll-Over Potential	$\dfrac{\frac{H-h}{2} + h}{T}$
Wind Disturbance Potential	$\dfrac{f(A,H,h,L)}{W} = \dfrac{\text{Side Area}}{W}$
Static Margin Empty (SM_E)[1]	$-\left[\dfrac{a-b}{2\ell}\right]$
Static Margin Loaded (SM_L)	$-\dfrac{a'-b'}{2\ell}$
$\Delta SM = SM_E - SM_L$	
Tire Pressure Imbalance	$\dfrac{W_F/(W-W_F)}{P_F/P_R}$
Horsepower to Weight Ratio	$\dfrac{HP}{W}$

[1]This expression for static margin assumes that the front and rear cornering stiffnesses are equal and roll effects are negligible.

Table 6.7. (Cont.)

Index Name	Symbol
Braking Instability, A [38]	$\dfrac{V-(\mu g \ell)/V}{a + \dfrac{I_z 32.2}{aW}}$
Lateral Acceleration Response Time (time to achieve 90% of steady-state A_y value)	τ_{ay}
Yaw Velocity Response Time	τ_{vy}
Roll Compliance, degrees per g	K_ϕ
Steering Sensitivity, lateral acceleration per 100° steering wheel angle	N_δ
Yaw Sensitivity, yaw angular acceleration per degree of steering wheel angle	r_δ
Characteristic Speed, mph	U_{ch}
Total Understeer, degrees per g	K
Time to Accelerate from 0 to 30 mph	T_{0-30}
Time to Accelerate from 0 to 60 mph	T_{0-60}
Time to Travel a Quarter-Mile from a Standing Start	T_q
Speed at End of Quarter-Mile from a Standing Start	V_q
Stopping Distance from 30 mph	d_{30-0}
Stopping Distance from 60 mph	d_{60-0}

Table 6.8. Limit Handling Performance Indices.

Index Name	Symbol
Limit Response to a Trapezoidal Steer Input	$R_s(\frac{1}{R})_{ave}\Big\|_{\sigma'} = 24$
Early Saturation of Cornering Capability	$\frac{\sigma'_{saturated}}{24}$
Change in Path Curvature Ratio with Respect to Steer Angle	$\frac{\partial\left[R_s(\frac{1}{R})_{ave}\right]}{\partial\sigma'}$
Peak Sideslip Response	$\beta_p\Big\|_{\sigma'} = 24$
Steer Angle at Which Vehicle Departs from Quasilinear Behavior	$\frac{\sigma'_{break}}{24}\Bigg\|\frac{\partial\left[R_s(\frac{1}{R})_{ave}\right]}{\partial\dot{\beta}_p}$ = Linear/Nonlinear Corner
Steering Wheel at Maximum Path Curvature Ratio	$\delta_{sw}\Big\|_{\sigma' = \sigma'}\Big\|_{R_s(\frac{1}{R})_{ave}\ max}$
Limit Wheels-Unlocked Deceleration Capability in Straight-Line Braking	$(A_x)_{ave}\Big\|_{St.Line}$
Product of Heading Error and Lane-Change Displacement Error at the End of a 2-sec. Lane-Change Maneuver	$(\Delta)(\Delta\psi)\Big\|_{t = 3.4,\ V_0 = 45\ mph,\ 60\ mph}$
The Average of the Product of Heading Error and Lane-Change Displacement Error for Left and Right Lane-Change Maneuvers	$\frac{(\Delta)(\Delta\psi)_L + (\Delta)(\Delta\psi)_R}{2}$

Table 6.8. (Cont.)

Index Name	Symbol
The Difference Between the Products of Heading Error and Lane-Change Displacement Error for Left and Right Lane-Change Maneuvers	$(\Delta)(\Delta\psi)_L - (\Delta)(\Delta\psi)_R$
The Integral Error from Perfect Performance in Lane-Change Displacement and Sideslip Angle Over a Range of Normalized Heading Angles (see Table 6.2 item (7)(a) for the definition of the variable Φ)	$\int_2^{18} \Phi d\sigma' \Big\vert_{V_o=45 \text{ mph},\ 60 \text{ mph}}$
The Average of the Integral Lane-Change Error for Speeds of 45 mph and 60 mph	$\dfrac{\int_2^{18} \Phi d\sigma' \Big\vert_{V_o=45} + \int_2^{18} \Phi \ \sigma' \Big\vert_{V_o=60}}{2}$
The Response to a Two-Second Lane Change as Quantified by the Product of Lane-Change Displacement Error and Peak Sideslip Angle.	$\sum_{\sigma'=2}^{18} (\beta_p)(\Delta) \Big\vert_{V_o=45 \text{ mph},60 \text{ mph}}$
The Average Response to a Two-Second Lane Change at 45 mph and 60 mph	$\dfrac{\sum_{\sigma'=2}^{18}(\beta_p)(\Delta)\Big\vert_{V_o=45} + \sum_{\sigma'=2}^{18}(\beta_p)(\Delta)}{2}$
Roll Response Under Large Side Forces as Quantified by the Product of the Average Peak Roll Angle in N Tests Times the Maximum Peak Roll Angle.	$\left(\frac{1}{N}\sum_{i=1}^{N} \phi_p\Big\vert_i\right)\left(\phi_p\Big\vert_{max}\right)$

Table 6.8. (Cont.)

Index Name	Symbol
Maximum Deceleration in a Turn Prior to Wheel Lock Up	$(A_x)_{ave}\Big\rvert_{Turn}$
Average of Maximum Deceleration in a Turn Performance for Right and Left Turns	$\dfrac{(A_x)_{ave}\big\rvert_R + (A_x)_{ave}\big\rvert_L}{2}$
Curve Following During Braking as Quantified by the Quotient of the Peak Value of the Average Path Curvature Ratio and the Corresponding Average Deceleration	$\dfrac{(A_x)_{ave}}{\left[R_o(\frac{1}{R})_{ave}\right]_{peak}}$
Roadholding in the Presence of Road Roughness as Quantified by Path Curvature Ratio	$R_o(\frac{1}{R})_{ave}$

6.2.4 Design Parameters Corrected for Loading. Since it is clear that in-use factors such as loading and tire inflation pressures will act to give a motor vehicle different handling properties than are implied by the parameters and indices defined in Tables 6.6 and 6.7, certain parameters and performance indices have been redefined so as to account for conditions prevailing at the time of the accident. Table 6.9 indicates the extent to which design parameters and performance indices based on curb weight loadings can be recomputed to reflect the influence of in-use variables or service factors. The utility and practicality of this approach remains to be demonstrated, however.

6.2.5 Vehicle Handling Data File. As has been implied earlier, the vehicle handling parameters and indices listed in Tables 6.6, 6.7, and 6.8 represent both the state of the art and the compromise that must be made between what is desired and what is attainable. Although there is a limited body of experience that relates some specific indices to issues of controllability, very little is known on the relationship between the tabulated indices/parameters and the accident record.

In this investigation, it was felt that an effort should be made to demonstrate the practicality of generating a vehicle handling data file. Further, as will be discussed in Section 7, it was also felt that some effort should be made to demonstrate the utility of such a file in establishing correlations between indices and accident rates even though the available rate data cannot be corrected for exposure and other confounding variables. Accordingly, considerable effort was devoted to collecting and organizing an accessible computer file containing data corresponding to the vehicle parameters and indices listed in Tables 6.6 and 6.7. Since the data are quite extensive and voluminous—covering a large number of makes, models, and model years—the data are not documented in this report. However, the data can be made available either as a listing or in card form at a nominal cost to parties that request it. Alternatively, the data file can be accessed by outside organizations through the University of Michigan computer system.

Table 6.9. Design Parameters and Performance Indices Corrected for Loading.

Parameter Name	Symbol
Actual Weight	W_A
Actual Weight on Front Axle	W_{FA}
Actual Weight on Rear Axle	W_{FR}
Actual Yaw Moment of Inertia	I_{ZA}
Actual Non-Dimensional Yaw Moment of Inertia	$\dfrac{I_{ZA}}{\left(\frac{W_A}{g}\right)\ell^2}$
Actual Weight Distribution	$\dfrac{W_{FA}}{W_A}$
Actual Brake Torque Imbalance	$\dfrac{\Gamma}{\frac{W_{FA}}{W_A} \times 100}$
Actual Static Margin (SM_A)	$-\left[\dfrac{a'_A - b'_A}{2\ell}\right]$
Actual Tire Pressure Imbalance	$\dfrac{W_{FA}/(W_A - W_{FA})}{P_F/P_R}$
Actual Side Area to Weight Ratio	$\dfrac{\text{Side Area}}{W_A}$
Actual Side Area to Yaw Moment of Inertia Ratio	$\dfrac{\text{Side Area}}{I_{ZA}}$
Horsepower to Weight Ratio (From VIN Number)	HP/W_A
Ratio of Actual Radius of Gyration to Wheelbase	$\sqrt{\dfrac{I_{ZA}}{W_A}}/\ell$

7.0 STATISTICAL ANALYSIS AND DATA COLLECTION METHODOLOGY

From earlier discussions, it should be clear that the task of determining the role of vehicle handling in accident causation will indeed be difficult. A methodology is needed which currently does not exist. Data that is not generally available will have to be collected. Since the required activities are time-consuming and costly, a plan is needed which will yield the necessary data and produce the needed results in an efficient and timely manner.

The methodology outlined here is based on using three or, perhaps, four sets of data. The main three sets, in broad terms, can be entitled:

a. Vehicle Exposure to Risk Data
b. Accident Data
c. Vehicle Handling Data

The fourth data set is less tangible than these three, but it could prove to be the most important factor of all in the accident process, or, on the other hand, might prove to be unimportant. This latter set of data will be called "Vehicle Image Risk Data." In the context of this study, "Image Risk" is a term which alludes to those vehicle characteristics which project a particular "image" to its driver (e.g., "macho," "sporty," "reserved," "sedate," etc.), namely, those characteristics which suggest that the vehicle is highly controllable and roadworthy. It is hypothesized that this image, in turn, influences the "risk" assumed by the driver in operating his vehicle, as determined by speed, headway maintenance, braking delay tendency, etc.

Some of the more important points to be addressed in establishing the above-defined data libraries are "how much data is needed and in what detail?" Clearly, the answers are dependent upon the refinement with which the relationship between vehicle handling and accident causation is to be determined. For example, if one is interested in knowing which car models have the highest accident rates, that is one level of refinement. If the question is:

> "Which car models have the highest accident rates given that each model is driven by an identical population of drivers?"

then that is a second, but more refined question. Further, if the question is:

> "Which car models have the highest accident rates given that (1) each model is driven by an identical population of drivers, and (2) each model is driven in an identical risk scenario (i.e., the same traffic, roadway, and environmental conditions)?",

we have a third level of refinement. And, finally, we could ask,

> "What car models have the highest accident rates given that (1) each model is driven by an identical population of drivers, (2) each model is driven in an identical risk scenario, and (3) each model has an identical image risk?",

clearly, an even higher level of refinement.

In addition to these levels of refinement of the general question posed above, uncertainties can arise in attempting to breakdown the general question of "what?" to that of "why?" Rather than being concerned with accident rates involving a particular model, a more specific question of interest to this study would be:

> "What is the relationship between different levels of understeer and accident rates on curves during wet weather, given that the rates for each level of understeer being examined are normalized for (1) driver population influences, (2) exposure influences, and (3) image risk influences?"

or alternatively,

> "What is the relationship between specific levels of 'brake line pressure versus pedal force' and accident rates for the striking vehicle in rear-end accidents, given that the rates for all 'pressure versus force' levels are normalized for (1) driver population influences, (2) exposure influences, and (3) image risk influences?"

As will become clear in the discussions that follow, the amount of data needed to answer each succeeding level of detail, or refinement, increases geometrically. On the other hand, without attacking the question in reasonable detail, it will be impossible to obtain an unbiased answer regarding the role of vehicle handling in accident causation. Nevertheless, at this point it is not possible to know the resources which can be allocated towards obtaining an answer; neither is it practical to predetermine the accuracy with which an answer will be considered acceptable. Therefore, the methodology presented here is couched so as to relate the requirements regarding detail and accuracy directly to the numbers of required data. In this way, the methodology can ultimately be tailored to the needs of the user.

In the subsections which follow, the statistical analysis aspects of the methodology shall be discussed first. These discussions are followed by specific recommendations regarding the kinds of data needed and the methods of collecting or acquiring same. Lastly, a trial application of the developed methodology is presented, as could best be done with the data that are available.

7.1 Statistical Analysis

Any investigation into the relationship between a variable and the incidence of traffic accidents must start with a hypothesis concerning that variable's role in the accident process. An accident can be considered the culmination of a chain of errors of omission and/or commission on the part of the driver, the vehicle, the roadway, and unfortunate circumstances. Since handling characteristics affect a vehicle's ability to maneuver in avoiding an accident, such characteristics are presumed to influence the last pre-collision act of this chain. One measure of the effectiveness of vehicle handling in accident avoidance, then, would be the probability of having an accident, given that a vehicle is "in imminent danger of collision" as a result of prior causative factors.

Although there is no arguing that accident probability is an appropriate measure, there is also no arguing that it is impractical. There is virtually no practical way of determining how many "in imminent danger of collision" situations occur in a given population of vehicles over a period of time. An alternative measure is the number of accidents per mile driven, i.e., the raw accident rate.

There is one outstanding problem in using raw accident rates as a proxy for the probability of an accident, however. The difficulty lies with the fact that not every mile driven exposes a vehicle to the same number of hazards. How a vehicle is driven, the character of the road, the weather, light conditions, and many other factors affect the number of "in imminent danger of collision" situations which are encountered in that mile. For example, one would expect more hazardous encounters per mile on an icy street in rush hour than on a dry, sparsely traveled freeway. To achieve objective validity, comparisons between various vehicle make/models, handling related design parameters, or performance indices should be drawn on the basis of <u>true</u> accident rates. The effects of all confounding factors should be accounted for, and the raw accident rates adjusted accordingly. A technique which can be used in carrying out these adjustments is called "indirect standardization."

7.1.1 <u>Indirect Standardization</u>. Indirect standardization [39] is a technique based on the assumption that, when considering a particular vehicle class, the accident rate of that vehicle class is due, in part, to the rates associated with the types of drivers and environmental conditions under which the vehicles are operated. It could be, for example, that a particular vehicle is driven primarily by irresponsible and reckless speeders. Such a class would no doubt exhibit a high accident rate, but not necessarily because the vehicle itself is poorly designed. By adjusting the rate to account for these drivers, a more accurate reflection of the true rate is obtained. This adjustment process is outlined below.

Let

R_k = raw accident rate for a given vehicle class k[1]

r_{Sj} = specific accident rate for factor class j[2]

R_S = overall rate for entire population

M_{kj} = mileage for a given vehicle class k and factor class combination j

The first calculation to be made in indirect standardization is the overall rate that would obtain if the specific rates for the factor combination were applied to the given vehicle class, i.e.,

$$R'_k = \frac{\sum_j r_{Sj} M_{kj}}{\sum_j M_{kj}} \tag{7.1}$$

It follows that the indirect adjusted rate is

$$R_k^{\text{indirect}} = R_k^{\text{ind.}} = R_S \frac{R_k}{R'_k} \tag{7.2}$$

Note that this scheme requires that accident rates be known for all vehicle classes and all factor combinations, but not for all combinations of classes and factors. Mileage figures for <u>all</u> combinations of classes and factors are required, however.

---

[1]"Vehicle class" refers to the set of vehicle make, model, model year, and other appropriate new car characteristics that make one vehicle unique from another.

[2]"Factor class" refers to any combination of exposure factors that uniquely describe the conditions under which a vehicle is driven.

In practical terms, the basic technique of indirect standardization can be illustrated through the use of Figure 7.1. This figure is an example data sheet which shows accident rates as such rates are related to k vehicle classes (R_1, R_2, R_3,....,R_k) in the right column and j factor combinations (r_{S1}, r_{S2}, r_{S3},...,r_{Sj}) in the bottom row. The mileage estimates, M_{kj}, for combinations of vehicle and factor classes are given in the cells of the matrix. An example of the use of indirect standardization as applied to existing accident and exposure data is presented in Appendix C.

7.1.2 Population Size. The "population" from which samples of accident and exposure data are to be derived is defined to be the number of miles driven by a group of vehicles over a given time period within a selected geographic area. The size of this population (of miles) can be determined by considering each vehicle-mile driven to be an "experiment," the result of which is either an accident or no accident. The total number of such experiments (or miles) required by a given analysis will be the required population size. The required sample size, on the other hand, will also be a function of the desired accuracy of the results.

To derive a relationship between population size and accuracy, we should note, first, that if the circumstances of every accident and every mile traveled were known exactly, and if this information were available for analysis, then questions of accuracy would be academic. Answers would be as exact as possible. In practice, of course, financial limitations almost always prevent the acquisition of complete information, and hence structured sampling techniques must be employed. When only a part of a data population is sampled, however, the resulting analysis performed on the data becomes less accurate. There is a tradeoff, then, between sample size and accuracy. Sophisticated sampling methods can minimize the accuracy loss, but complete accuracy, consistent with sampling an entire population, can never be achieved irrespective of the sophistication employed in a partial sampling procedure. Since neither the financial resources,

NSC AGE	14yr								15yr								16yr							RAW ACCIDENT RATE
SEX	MALE				FEMALE				MALE				FEMALE				MALE					LE		
ROAD ALIGNMENT	CURVE		STRAIGHT		CURVE		STRAIGHT		CURVE		STRAIGHT		CURVE		STRAIGHT		CURVE		STRAIGHT			STRAIGHT		
WEATHER	DRY	WET	DRY	WET	DRY	WET	DRY	WET	DRY	WET	DRY	WET	DRY	WET	DRY	WET	DRY	WET	DRY	WE		DRY	WET	
VEHICLE CLASS																								
VEHICLE #1	M_{11}	M_{12}	M_{13}	M_{14}	.	.	.	.	.	.	.	.	.	.	.	.	..	.	.			.	M_{1C}	R_1
VEHICLE #2	M_{21}	M_{22}								.											.		M_{2C}	R_2
VEHICLE #3	M_{31}		.							.													.	R_3
" #4	.			.						.													.	R_4
"	.				.					.													.	.
"	.	.				.				.													.	.
"	.	.	.	.	.	.	.	.	.	M_{kj}	.	.	.	.	.	.	.	.	.	.	.	.	.	.
"	.									.													.	.
	.									.													.	.
										.														
	.																							
" #H	M_{H1}	M_{H2}	M_{H3}	.	.	.	.															.	M_{HC}	R_H
SPECIFIC ACCIDENT RATES	r_{S1}	r_{S2}	r_{S3}	.	.	.	.	.	.	r_{Sj}	.	.	.	.	.	.	.	.	.		.	.	r_{SC}	R_S

Figure 7.1. An example data sheet illustrating the use of indirect standardization.

nor the desired accuracy of results are currently known, it appears appropriate to structure the methodology in the form of a tradeoff between accuracy and population size.

On considering a mile driven to be an "experiment," the establishment of an accident record is equivalent to observing many experiments in which an accident may, or may not, have resulted.

If the number of accidents is divided by the number of miles driven (number of experiments), a statistic is derived which is called a proportion. This statistic has a distribution, that is, if the whole procedure were repeated under identical circumstances, the proportion would likely be different. Thus, the proportion statistic is a random variable which has an approximate normal distribution, with variance equal to $P(1-P)/n$, where n is the number of "experiments" (or miles) and P is the true proportion. (For this expression for variance to be a good approximation, the number of accidents should be greater than 5.) This situation means that even if the number of accidents and the number of miles driven by a population of vehicles were known exactly, the observed accident rate would still be only an <u>estimate</u> of the true rate.

The variance of the proportion can be used to derive the order of magnitude of n as a function of the desired accuracy of the resulting rates. In particular, the 95% confidence interval* encompassing an estimated rate would have a value approximately equal to:

$$\text{C.I.}(r) = 3.92 \sqrt{\frac{r(1-r)}{n}} \tag{7.3}$$

where r is an observed rate. On rearranging (7.3), it is seen that

$$n = \left[\frac{3.92}{\text{C.I.}(r)}\right]^2 r(1-r) \tag{7.4}$$

*A 95% confidence interval represents an interval encompassing an observation within which the true rate would likely lie, with 95% probability.

where C.I. can now be treated as the desired size of the confidence interval.

In order to illustrate the utility of Equation (7.4) in designing a methodology for establishing the role of handling in accident causation, consider the case in which

$$r = 2.5 \text{ accidents}/10^6 \text{ miles}$$

and the desired size of the confidence interval is

$$\text{C.I.}(r) = 3.92 \text{ accidents}/10^6 \text{ miles.}$$

From Equation (7.4), we find that $n \approxeq 2.5 \times 10^6$ miles.

With an estimate of the number of miles (or "population") which need to be included in the study, it is then possible to estimate the size of the accident sample and the length of the study period. As a point of reference, the drivers of Seattle, Washington, drove approximately $7{,}000 \times 10^6$ miles in the year 1970. Assuming an accident rate of approximately 2.5 acc/10^6 miles (which is about what would be expected according to the preliminary results of Appendix C), the following table can be constructed which relates confidence interval to mileage sampled.

Table 7.1. Accident Rate Confidence Interval vs. Miles Driven

C.I.(r)	n Required (r = 2.5 acc/10^6 miles)
0.25 acc/10^6 miles	614.7 x 10^6 miles
0.5 acc/10^6 miles	153.7 x 10^6 miles
1.0 acc/10^6 miles	38.4 x 10^6 miles
2.0 acc/10^6 miles	9.6 x 10^6 miles
5.0 acc/10^6 miles	1.5 x 10^6 miles

The above analysis and computations show how the accuracy of the estimated accident rate depends upon the number of miles sampled of the total miles driven by the subject group of vehicles. Naturally, the more mileage data obtained, the better the resulting rate estimates. A point that should be stressed, however, is that the above-derived relationship between accuracy and mileage sampled is based on the assumption of exact knowledge of the number of accidents and number of miles driven in each category—something which is impossible to obtain before the fact. Thus the sample size figures obtained for each level of accuracy represent <u>lower bounds only</u>. Their use should only be to serve as benchmarks for experimental planning purposes.

In practice, a geographic locale and a study period would be selected, and neither the miles driven, nor the number of accidents sustained by the drivers within the locale would be known exactly beforehand. Both would have to be estimated. The true accuracy versus sample size relationship is therefore complicated even further by this degree of uncertainty. In effect, an experimental process is being observed where the number of experiments (i.e., a mile driven) is not known exactly and can only be estimated. The number of these experiments which result in accidents is also subject to estimation.

The convolution of all these random processes is too complicated to analyze. Instead, a separate analysis is presented showing the effects of accident sample rate and mileage sample size on the accuracy of the resulting accident rates. A complete analysis is not presented, but enough detail is provided to allow intelligent decisions to be made concerning sizes of vehicle populations, accident samples, and mileage samples.

The figures presented in Table 7.1 are based on a single accident rate estimate. Since accident rates for all vehicle and factor combination classes are needed, these mileage values must be multiplied by either the number of vehicle classes, H, or the number of factor classes, C, depending on which is the larger. (If H were larger than C, for example, and the data sample were large enough to yield a sufficient number of entries per class when divided evenly into H parts, the sample will <u>a' priori</u> be large enough when divided evenly into C parts.) For example, if there are 100 vehicle classes, 200 factor classes, and a C.I.(r) equal to 0.25 acc/10^6 miles is desired (an approximate error of 5% in estimating the true accident rate), then the Max(H, C) = 200, and $(200)(614.7 \times 10^6) = 122{,}900 \times 10^6$ miles would have to be driven by the vehicle population being observed during the study period. At a rate of 2.5 acc/10^6 miles, a total of 307,300 accidents would have to be reported in the study period for the selected population.

Knowing the population size required (i.e., the number of "experiments") and the number of miles per year which are expected to be driven by a population of vehicles, it is then possible to determine the length of the required study period. For example, if the geographic locale of the study area were confined to Seattle, Washington, and all vehicles in this area were of interest, then the study period would have to be almost 18 years long ($122{,}900 \times 10^6$ mi. $\div$ $7{,}000 \times 10^6$ mi/yr). Obviously, a larger geographic area or a relaxation in accident rate accuracy would be required to obtain a study period of reasonable length. As will be noted later, a study period of reasonably short duration is also desirable to insure that the handling characteristics of the vehicles involved in the selected population remain reasonably constant over time and close to their measured condition.

It should be noted, of course, that these numbers are approximations since it has been assumed that r = 2.5 acc/10^6 miles and that a uniform distribution of mileages exists among all cells. This last assumption is very probably not correct, but since the interest here is only in determining the order of magnitude of n, the approximations should be sufficient for the purpose of determining a population size.

7.1.3 Accident Data Sampling Frequency. Once the population size is determined, the next step is to determine the sampling frequency at which accident data is to be collected.

Since the accident rate varies linearly with the number of accidents, errors in estimating the number of accidents in a cell also linearly influences the estimated accident rate for that cell. When an accident is investigated and assigned to a cell, the accident will be classed according to the combination of vehicle type and factor values involved. The overall estimate of the number of accidents in a particular cell is formed by dividing the sampled number in the cell by the sampling frequency. So if the sample frequency were 100% (all accidents investigated), the sample number of accidents in the cells would be exactly the statistic desired. If only 1% were sampled, the estimate would be 100 times the sample number. Any error in the overall estimate comes mainly from the process of extrapolating from the sample to the overall number of accidents.

If the distribution of accidents among all cells is random and there are d cells, one would expect a proportion of 1/d of the total accidents to fall into each cell. In reality, of course, for any finite number of accidents, all cells will not have the same number of entries, even if the likelihood for an accident falling into a given cell is equal for all cells. In fact, the proportion of the total accidents found in a given cell would be a random variable with an expected value of 1/d and a standard deviation approximately equal to:

$$\sqrt{\frac{\left(\frac{1}{d}\right)\left(1 - \frac{1}{d}\right)}{m}} \; ; \quad \text{if } \frac{m}{d} \geq 5. \qquad (7.5)$$

where

m = total number of accidents investigated in a fractional sample

d = maximum value of H or C, the number of vehicle or factor classes.

(The derivation of Equation (7.5) is based on the assumption that the values of the cell entries have a normal distribution. In actuality, the distribution of this statistic is of the Poisson type, and when $m/d < 5$, the expression given by Equation (7.5) is inaccurate. On the other hand, a Poisson distribution is cumbersome to use for large values of m/d and the normal distribution is easy to use and is an excellent approximation in this latter region.)

The 95% confidence interval about an observed accident rate is 3.92 times the standard deviation. For a fractional sampled population, this confidence interval for the proportion of accidents in an individual cell is given by:

$$\text{C.I.(A)} = 3.92\sqrt{\frac{\left(\frac{1}{d}\right)\left(1 - \frac{1}{d}\right)}{m}} \qquad (7.6)$$

The confidence interval for the estimated number of accidents for the entire vehicle population is proportional to C.I.(A), where the proportion equals the inverse of the sampling frequency. That is, if C.I.(A) is the confidence interval of the fractional sample, then the confidence interval for the entire population is:

$$\text{C.I.} = \frac{1}{x}\,[\text{C.I.(A)}] = \frac{1}{x}\,(3.92)\sqrt{\frac{\left(\frac{1}{d}\right)\left(1 - \frac{1}{d}\right)}{m}} \qquad (7.7)$$

where

x = sample rate = m/Total Number of Accidents

This last expression is, of course, an approximation since an equal distribution of accidents among classes is assumed. Nevertheless, the expression is useful in that it can be used to estimate order-of-magnitude values for x.

As an example, consider a vehicle population that experiences approximately 5,000 accidents in a year. If there were 100 factor combinations within which these accidents could be classified, then the following relationship between accident sample frequency and confidence interval would exist, a la Equation (7.7):

Sample Frequency, x	C.I. (Accidents)	% Error (C.I./2m)
1%	200.0[1] (275.7)[2]	2.0
5%	120.0[1] (123.3)[2]	1.2
10%	87.2[2]	0.9
20%	61.6[2]	0.6

The associated accident rate confidence intervals would be directly proportional to the above confidence intervals for accidents alone because of the linear relationship between accidents and accident rates.

7.1.4 Exposure Data Sampling. The mileage exposure data, M_{kj} (see Figure 7.1), serve two purposes, namely, to (1) assist in determining accident rates for all factor and vehicle classes, and (2) provide mileage estimates for all combinations of both factor classes and vehicle classes as used in indirect standardization. There are obviously many more separate estimates required for this latter purpose (i.e., the first purpose calls for mileage estimates for the right column and lower row of Figure 7.1, while the second purpose calls for estimates for all interior matrix elements). Therefore, the sample sizes necessary for mileage estimates will always be more than adequate for determining the accident rate estimates R_k and r_{Sj} (again, see Figure 7.1). For this reason, the

[1]Computed by the use of the Poisson distribution which is a better estimate of the confidence interval for small values of m/d.

[2]These values were computed by Equation (7.7) where a normal distribution was assumed, but the ratio m/d here is less than 5 and the values are not as accurate as those computed by the Poisson distribution.

estimated accuracy of the accident rates will always be primarily a function of the error in the mileage estimates.

The important factors in collecting exposure data are (1) the rate at which drivers are to be sampled for reporting the mileage to which their vehicles have been exposed, and (2) the length of the period over which drivers will be asked to recall this "mileage exposure." (This latter period will be denoted as the "Interview Recall Period." It will be assumed at this point that mileage exposure data will be obtained from driver interviews at driver license renewal centers and from trip logs obtained through mailed surveys. Justification for this assumption will be presented later.) At first glance, the driver sample rate and the interview recall period used to establish exposure might appear to be purely procedural questions. Both factors are, however, directly related to the accuracy of the expected results.

It has been pointed out that when the number of variables or the number of factor levels increases, the number of required mileage estimates increases also, and more data will be needed. To see how fast these needs grow, consider just five variables, each with four levels. The number of separate estimates required would be 4^5 or 1,024. If it can be assumed that there is independence between some of the variables, then this number could be reduced. (The assumption of independence may not be realistic in many cases, however.) The exponential increase in data requirements should be kept in mind when variables are being selected. Where independence between variables is assumed, mileage estimates for all combinations of variables do not have to be estimated, as the mileages can be estimated by multiplying the marginal distributions of the factors involved. For example, if 20% of the miles are driven at night, and 10% in wet weather, then 2% (.20 x .10 = .02) of the miles are driven on rainy nights.

7.1.5 Accident Rate Accuracy. The accuracy of mileage estimates is a complicated issue. Of course, the real objective is to obtain accuracy in the indirectly standardized vehicle accident rate—the mileage estimates are only incident to this.

On assuming that all rates used in Equation (7.1) are known exactly (viz., R_S, R_k, R'_k), the only source of inaccuracy that remains is the M_{kj} figures. If these latter quantities are estimated, then these estimates are random variables and can be used to trace backwards from the desired confidence interval width for the indirectly standardized rates, to the corresponding accuracy required of the mileage estimates, and thence to the mileage population size. Thus in the following analysis, M_{kj}, as used in Equation (7.1), will be treated as a random statistic, the estimated mileage in the $kj^{\underline{th}}$ cell for the entire population.

On recalling Equation (7.1), it can be noted that the mileage estimates affect the adjusted accident rate, R'_k, for a given vehicle model which is in the denominator of the R_k^{ind} statistic—Equation (7.2). This means that the errors in R_k^{ind} vary inversely with errors in R'_k. For example, assuming that R_S, R_k, and the true value of R'_k are each 2.5 acc/10^6 miles, it can be seen from the following table that the errors in R_k^{ind} are very sensitive to negative errors in R_k, but not so sensitive to positive errors. (All units are in acc/10^6 miles.) Since there is no way of controlling the sign of

Error in R_k	R_k	R_k^{ind}	Error in R_k^{ind}
-1.5	1.0	6.3	+3.8
-1.0	1.5	4.2	+1.7
0	2.5	2.5	0
+1.0	3.5	1.8	-0.7
+2.0	4.5	1.4	-1.1

the errors, it appears advisable to keep the accuracy of R_k to within about ±1 acc/10^6 miles. The confidence interval of R_k^{ind} can then be approximated by that of R_k.

Referring again to Equation (7.1), it will be noted that R_k' can be thought of as being individual mileage estimates for each factor combination associated with vehicle class k where the weights are the standard accident rates of each factor class, i.e.,

$$R_k' = \frac{\sum_j r_{Sj} M_{kj}}{\sum_j M_{kj}} \tag{7.8}$$

If now it is assumed that all r_{Sj}'s are constants equal to 2.5 acc/10^6 miles for all j, and all the estimated M_{kj} statistics are independent, then the 95% confidence interval for R_k' can be related to the M_{kj} (that is, assuming estimates of M_{kj} are normally distributed) by:

$$\text{C.I.}(R_k') = 3.92 \sqrt{r_{Sj}^2 \sum_j V\left(\frac{M_{kj}}{\sum_j M_{kj}}\right)} \tag{7.9}$$

where the symbol $V(\ )$ implies the variance of a quantity.

Since the M_{kj} are estimates of the <u>total</u> population mileage for particular combinations of vehicle and factor classes, values for these quantities must be determined from the sample estimates by multiplying corresponding sample mileages by the inverse of the sample frequency. Specifically, if

- S = Mileage exposure sample frequency (i.e., the percent of the entire population sampled)
- L = Number of recall intervals in the study period (e.g., L = 52 if the recall interval is one week and the study period is one year)
- $\overline{m}_{kj}$ = average mileage of the sample in the kj cell

(i.e., $\bar{m}_{kj} = \dfrac{\sum_{\ell=1}^{g} m_{kj\ell}}{g}$ and g is the number of individual samples falling into a given cell),

then we can write the following:

$$M_{kj} = \frac{L\,\bar{m}_{kj}}{S} \tag{7.10}$$

and

$$V(M_{kj}) = \frac{L^2 V\left(\bar{m}_{kj}\right)}{S^2} \tag{7.11}$$

Thus, if L = 52 and S = 10%, then

$$V(M_{kj}) = 270{,}400\ V(\bar{m}_{kj}).$$

Finally, there is the relationship between the variance of the individual cell sample mileage estimates, the driver recall interval for estimating miles traveled, and the sampling frequency for selecting drivers to be interviewed. It seems reasonable that the shorter the recall period, the more accurate the respondent's mileage estimate. It would be both easier and more accurate to recall mileage for one week than for a whole month, for example. As a point of reference, the data used in connection with the preliminary studies reported in Appendix C (although not mentioned there) show a sample standard deviation of 500 miles for the estimated mileage statistic as reported by <u>individual</u> drivers for a one-month recall period. Using 500 miles for the sample standard deviation, and presuming now that g drivers fall in each cell, then the sample standard deviation for the <u>average mileage</u> of these g individuals will be $500/\sqrt{g}$. Thus, in approximate terms,

$$V\left(\bar{m}_{kj}\right) = \frac{VAR}{PS/CH} \tag{7.12}$$

where

VAR = the sample variance of the exposure mileage for a group of drivers falling into a particular factor and vehicle combination

P = the total population of drivers from which the sample is extracted

S = the sample rate

C = the number of factor classes

H = the number of vehicle classes

It will be noted that the term PS in Equation (7.12) represents the total number of drivers interviewed, CH equals the total number of cells (see Figure 7.1), and PS/CH equals the number of people interviewed per cell. If it is assumed now that the drivers being interviewed are uniformly distributed through all cells, and if it is further assumed that

VAR = (500 mi.)^2

P = 10^6 drivers

S = 1%

C = 100

H = 10

then

$$V\left(\bar{m}_{kj}\right) = \frac{(500)^2}{(10^6)(10^{-2})/(10^2)(10)} = 25 \times 10^3 \text{ mi.}^2$$

Finally, by combining Equations (7.11) and (7.12)

$$V\left(M_{kj}\right) = \frac{L^2 CH(VAR)}{PS^3} \tag{7.13}$$

Equation (7.13) relates the variance of the estimated mileage driven by the <u>entire</u> population falling into cell kj to the variance of the response of the <u>sample</u> population to the question: "How many miles were driven under the conditions of cell kj during the response period?" This relationship can be used in determining the size of the mileage sample and the length of the mileage recall period.

Unfortunately, the functional link between the estimated cell variances, $V\left(M_{kj}\right)$, and the accuracy of indirectly standardized rate, R_k^{ind}, cannot be carried further. Ultimately, it would be desirable to express the accuracy of the indirectly standardized rates as a function of:

1. Population size
2. Length of study period
3. Accident sample size
4. Mileage sample size
5. Mileage recall period

The resulting relationships are too complicated for complete analysis, however (e.g., variances of variances of estimates before the fact). This complexity is undoubtedly the reason why such relationships have not been developed heretofore.

7.1.6 <u>Accident Rate Analysis</u>. On assuming that the methods outlined above will be used to obtain accident rates which are free of confounding influences, the next step is to analyze these rates for dependence upon vehicle handling factors. Since statistical methods (namely, correlation analysis and stepwise linear regression techniques) are available and have been employed for this purpose, these methods need not be discussed further here. The reader is referred to Jones [1] for a directly applicable example.

While Jones' work is pioneering in the sense that he demonstrates a means for directly assessing the role of vehicle handling in accident causation, he was limited, unfortunately, to a group of 34 vehicles for which he was able to acquire handling data. This limitation led to uncertainties in the correlation analyses involving accident rates and handling variables. The correlation coefficients that Jones obtained were, in most cases, not statistically significant. Although statistical significance is not the "end-all" criterion for a demonstrated relationship between two variables, lack of same is certainly a less desirable situation than is otherwise the case.

The most direct way of increasing the chance that a statistically significant relationship can be found between two variables is to increase the number of data points available for analysis. In the present situation, increasing the number of data points means gathering vehicle handling data on a larger group of vehicles. The number of vehicles required can be determined by examining Jones' correlation plots. Such an examination leads to the observation that at least 70 vehicles would be necessary to yield statistically significant results for many of the handling variables which he considered. For some handling variables, it appears that as many as 100 vehicles would be needed.

Since the handling variables recommended for analysis in this methodology are more diverse than those considered by Jones, it would appear that handling data will have to be obtained for at least 100 vehicles if the methodology proposed herein is to be implemented. Although such a number may appear to be conservative, it should be kept in mind that the relationship between vehicle handling parameters and accident causation and/or involvements is essentially unknown. Further, as will be pointed out later, in order to guarantee a reasonable chance for success in this endeavor, the accident data, exposure-to-risk, image risk, and vehicle handling data should be collected within a two-year period. If a lesser number of vehicles are measured for handling properties initially and more handling data is found to be necessary later, difficulties could arise in finding vehicles which have not aged or deteriorated to the point where their handling properties have changed. In simple words, the measurement of too few vehicles will create a very high risk of producing results that will be inconclusive.

7.1.7 Summary of Statistical Analysis. Clearly, a methodology for demonstrating the role of vehicle handling in accident causation involves a host of complex analyses to derive findings that are both conceptually and statistically meaningful. The major accomplishments with respect to fulfilling the statistical analysis requirements of this study are believed to be the following:

1. The accuracy of the accident rates has been defined as a function of the mileage driven in the selected geographic locale during the study period, given that the miles driven and accidents sustained are known exactly.

2. A relationship has been developed relating the accuracy of the accident estimates to the accident sample size.

3. An analytical formulation has been developed for tracing the effect of the variance in the individual mileage estimates (for the mileage recall period) on the mileage estimates for the entire population during the study period.

Although the analyses fall short of completely specifying the overall relationships desired, they constitute tools that are essential to planning the data collection programs that are required to establish the role of vehicle handling in accident causation.

7.2 Data Collection Plan

As pointed out in the introduction to Section 7.0, the three, or four, sets of data required to implement a methodology for determining the role of vehicle handling in accident causation are:

a. Vehicle Exposure-to-Risk Data

b. Accident Data

c. Vehicle-Handling Data

and possibly

d. Vehicle Image-Risk Data

Obviously these four data sets are quite diverse. Although each data set will require different methods of acquisition, each individual collection program must be coordinated with the other three. In the subsections that follow, it is recommended that exposure-to-risk data be collected by means of driver surveys. It is recommended that accident data be collected in the usual manner, namely, by means of accident reports. The acquisition of vehicle-handling data will clearly require an extensive measurement program. Finally, the acquisition of vehicle image-risk data will require that surveys be made of speed, lane keeping, and headway maintenance patterns (under everyday traffic conditions) for each of the vehicle models included in the study.

The data collection tasks will have to be coordinated in several ways. First, all four sets of data must be limited to a specific set of vehicles—a group of specific make, model, and model year classes. Second, all data elements collected in the vehicle exposure-to-risk studies will also have to be collected in the accident investigations. (On the other hand, there are certain accident data elements which need not—and cannot—be collected in the exposure studies.) Third, all four data collection programs will have to be carried out within a limited time period. Fourth, it appears that both the exposure-to-risk and the accident data (and perhaps the vehicle image-risk data) should be collected within the same geographic locale.

The need for limiting all four sets of studies to a specific set of vehicles stems from the requirement for comparing vehicle-handling properties with accident descriptors. Vehicle-handling data for almost all vehicle models is generally unavailable. Such data will have to be acquired through a structured measurement program. In order to minimize costs, the number of vehicle models to be measured will have to be limited. It is neither necessary nor advisable to measure all vehicles, but as has already been mentioned, a group of about 100 should be enough to provide statistical significance in subsequent regression analyses.

As has already been mentioned, the need for carrying out the data collection tasks within a limited time period is primarily influenced by considerations involving the validity of the vehicle-handling data. It is known that the handling properties of in-service vehicles can change drastically with time, primarily as a result of tire wear and tire replacement. Thus, if handling properties are to be compared in any meaningful way with accident statistics, the accident-involved vehicles should be relatively new, leading to the recommendation that involved vehicles should be no more than two years old, since beyond this age, most vehicles are equipped with replacement tires or possess OE tires that are heavily worn. Further, since it follows that the accident and exposure data must be collected during the same time period, it seems reasonable to recommend that the image-risk data be collected concurrently. The level of effort to be expended in these data collection programs should be based on the number of data elements required and on the advisability of constraining the study period to a period of no more than two years so as to minimize changes in the characteristics of the vehicle population.

The need to collect exposure-to-risk and accident data within the same geographic area is obvious. It makes no sense to collect exposure data in California and accident data in Iowa, for example, since driver and vehicle populations could be quite different in the two states, and, clearly, the driving environment is obviously different. Since the exposure data will be used to normalize the accident data, a one-to-one correspondence between the two is necessary.

Each of the required data collection programs is worthy of further discussion. Specific facets of these programs are treated below.

7.2.1 Collection of Vehicle Exposure-Risk Data. The accident rate statistic (i.e., accidents per mile) is influenced by many conditions and factors. An accident is a natural trigger for initiating a data collection activity. The conditions at an accident scene are recorded for law enforcement and legal purposes. But who records the conditions during normal driving? How many miles are driven under various weather, road, driver, and vehicle conditions? The acquisition of this type of information is much more difficult. In fact, there are no files of exposure data comparable to the extensive files that exist for accidents. Without exposure data, however, the computation of accident rates is not possible and any attempt to determine the role of vehicle handling in accident causation without exposure data will be unsuccessful. It follows that an exposure data file, tailored specifically to vehicle handling considerations, will be necessary.

The subject of exposure is not new. Much has been written about the topic [40, 41], and many schemes have been proposed for collecting exposure data, viz.:

1. Interviews with drivers at license renewal offices
2. Surveys of drivers using trip logs
3. Roadside surveys at check lanes
4. Indirect methods

Each of these schemes has its good and bad points.

A good discussion of the methods which involve the interviewing of drivers at license renewal offices is given in Reference 40. This method has advantages in that (1) a large amount of data per dollar can be acquired in terms of driver, vehicle, and roadway factors, and (2) the method is easier to apply than some of the other techniques. Further, the requirement for collecting data in a random manner can be readily accomplished. The drawbacks to the interview method are that drivers (1) do not always recall their driving experiences over the designated recall period as well as might be desired and (2) may give biased answers.

Conducting exposure surveys by requesting drivers to maintain trip logs yields much of the same type of information as does the interview at the licensing office. The uncertainties surrounding driver recall, and the attendant bias thereof, is eliminated, however. On the other hand, the trip-log method is much more expensive per datum collected in that compensation would probably have to be provided to respondents to ensure a sufficient and truly random response.

The theory of sampling [2] and the field application [42] of techniques involving roadside surveys at check-lanes is reasonably well in hand. The major benefit of the check lane method is that, if carefully done, the bias problem can be reduced or eliminated. On the other hand, collection problems can be very difficult. If vehicles are merely observed while passing an observation point, very little specific information can be obtained on the driver, e.g., sex and perhaps a crude guess of age. If vehicles are stopped at a police check-lane, more data are available, but the cost of such data is high, and the amount that can be collected is limited. Further, the need to sample in all weather and light conditions, and along all types of roads compounds the difficulty. Many separate check-lane locations will be required and sampling periods will have to encompass the entire 24-hour day. These requirements, for example, lead to check-lanes at night along freeways—an operation that is dangerous and probably not practical.

The idea behind indirect-exposure methods [41] is that the proportion of the various characteristics that are exhibited in the so-called <u>nonculpable</u> vehicles in a population of multiple-vehicle accidents is indicative of the proportion of these characteristics in the vehicle population as a whole. Although this idea may have some validity, there is a potential flaw in this concept which is particularly serious in a vehicle handling study. In effect, it may turn out that supposed "not-at-fault" vehicles contribute in a partial way to certain kinds of accidents as a result of properties or qualities that make them poorer avoiders of accident situations. Thus, the so-called "not-at-fault" vehicle may be a biased indicator of the properties of the vehicle population at large.

Four specific methods of collecting exposure data for the accident rate analysis have been mentioned along with some of the benefits and drawbacks of each. The selection of an appropriate method could be a significant research effort in its own right. Fortunately, however, much of the basic work has already been done. Specifically, Carroll [40] determined that a mailed questionnaire-type survey with attached trip logs, combined with interviews at license renewal offices, constitutes the best mileage estimation method. This recommendation is adopted here.

There are still several questions which must be answered before a full-scale exposure survey can be performed. Some of these questions relate to the information to be acquired in the questionnaire, some to the required sample size, and some to possible methods of inducing a high response fraction. It should be noted that Carroll [40] has already done considerable preliminary research with respect to the information to be acquired. On developing a questionnaire and evaluating it by means of a pilot survey, he proceeded to select three dependent variables related to risk and six independent variables related to vehicle, driver, and roadway descriptors, as listed in Table 7.2. Although Carroll argued rather effectively that these nine variables represent the best set to normalize <u>existing mass accident data</u>, there are several reasons why this set is not optimum for studying the role of vehicle handling in accident causation.

Table 7.2. Selected Exposure Variables from Carroll Study [40].

Dependent Variables	Levels on Questionnaire
Miles Driven Last 30 Days	Open
Miles Driven Last 7 Days	Open
Number of Accidents Last 3 Years	Open
Independent Variables	
Vehicle Type	7: Car, Small Truck, Large Truck, Tractor-Trailer, Bus, Taxi, Other
Driver Sex	2: Male, Female
Road Type	4: City Streets, Urban Freeways, Rural Freeways, Rural Roads
Light Condition	2: Day, Night
Driver Age	Open
Model Year	Open

First, it will be presumed that additional elements can be added to accident reporting procedures, so that the exposure data elements need not be restricted to information on existing accident forms. Next, it is obvious that the "Vehicle Type" variable, as denoted by Carroll, will have to be defined much more specifically than Table 7.2 indicates. Third, several other variables will have to be included which are strongly suspected of influencing accidents related to vehicle handling, e.g., road alignment, pavement surface condition (viz., wet, dry, bumps, chuck holes, etc.), driver experience, etc. It thus appears that the variables shown in Table 7.3 constitute a reasonable set, as an initial basis for developing a questionnaire. The wording of the questionnaire should, of course, be carefully developed so as to motivate the respondents and thus yield reasonably accurate and unbiased answers. Although it is not

Table 7.3. Recommended Exposure Variables for Vehicle Handling Analysis.

Driver Information

D.O.B.
Sex
Height
Weight
Corrective Lens Restriction

Occupation
Annual Income
Marital Status
Number of Children
Number of Vehicles Regularly Driven
Years Formal Education
Years Driving Experience
Formal Driving Education
Violations During Previous Twelve Months

Seat Belt Usage Practice

Vehicle Information

Vehicle No.____

Make
Model
Model Year
Number of Doors

VIN Number
Number of Engine Cylinders
Power Steering
Power Brakes
Automatic Transmission

Odometer Reading
Pressure At Which Tires Are Maintained, This Vehicle
Tread Depth At Which Tires Are Replaced, This Vehicle
Periodic Lubrication Practice, This Vehicle

Estimated Total Miles Driven This Vehicle
Estimated Miles Driven This Vehicle Last Twelve Months
Estimated Miles Driven This Vehicle Last Thirty Days
Estimated Miles Driven This Vehicle Last Seven Days
Number of Accidents With This Vehicle Last Three Years

Estimated % Travel on Rural Freeways, This Vehicle
Estimated % Travel on Urban Freeways, This Vehicle
Estimated % Travel on Urban Streets, This Vehicle
Estimated % Travel on Rural Roads, This Vehicle
Estimated % Travel as Part of Occupation, This Vehicle

Estimated % Travel in Darkness, This Vehicle
Estimated % Travel in Rainy Weather, This Vehicle
Estimated % Travel on Curved, or Winding Roads, This Vehicle
Estimated % Travel in Foggy Weather, This Vehicle

Running Speed Driving Habits, This Vehicle possible to define an appropriate questionnaire at this point in time, the steps for developing the questionnaire can be set down, viz.:

1. develop pilot-survey questionnaire using proposed variables
2. carry out pilot survey
3. analyze results by:
   a. evaluating pilot-survey questionnaire
   b. evaluating feasibility of pilot survey methods
   c. estimating costs of final survey
4. select final variables

and 5. revise questionnaire.

Given that these steps are carried out and the ensuing exposure survey is performed in a coordinated manner with the other data collection programs, exposure data suitable for normalizing the accident data and obtaining valid accident rates will result.

7.2.2 Accident Data Collection. There are several concerns which must be addressed with respect to collecting accident data for determining the role of vehicle handling in accident causation. First, as discussed in Section 7.1, upwards of 300,000 cases will be required. Second, as has been previously mentioned, the accident data should be acquired within a two-year period from a well-defined geographic area. Third, the data will have to be of sufficient quality and detail as required to examine questions related to vehicle handling. Finally, the accident-involved vehicles will have to be confined to the specific group for which vehicle handling data have been or will be acquired.

Collecting data on accidents within a two-year period virtually constrains the accident investigation to that of police agency reporting. As is well known, police reporting is frequently deficient, in both accuracy and detail. Nevertheless, there seems to be no other alternative but to develop a reporting system in which it is recommended certain specific elements of information are gathered by having the police use a supplemental report form. Clearly, the importance of accuracy will have to be impressed upon the police agencies who are collecting the data within a designated area.

The specific information additional to what is normally collected can be identified by first examining a typical accident reporting form used by police agencies, as is exemplified by the State of Michigan form shown on Figure 7.2 On comparing the data elements in Figure 7.2 with those listed in Table 7.3, and on considering other factors related to vehicle handling, we can identify the following informational elements as deserving of collection:

First Priority:

Vehicle

Vehicle Identification Number (VIN)

Model	Power Steering?
Number of Doors	Power Brakes?
Odometer Reading	Automatic Transmission?
Gas Gauge Reading	Number of Cylinders in the Engine

Driver

Height of Driver
Weight of Driver
Corrective Lens Restriction
Marital Status
Number of Children

} From Driver's License

Occupants & Payload

Estimated Weight Each Occupant
Estimated Weight of Cargo
Position of Cargo

Road Condition

Bumps or Potholes in Surface

ORIGINAL

UD-10 (Rev. 12/75) State of Michigan

OFFICIAL TRAFFIC ACCIDENT REPORT

Department Name | Number | DO NOT USE

Location

County Number | City Number | Twp. Number | Date | Time A.M. P.M.

ON Name | Route No. | Ft. Mi. N S E W | Intersection | Route No.

Vehicle #1

State | Drivers License | DOB | Hazardous Action | HBD | HN | Test

Driver No. 1 First M. Last | Address | City | State | Age | Sex | Inj

Year | Make | Type | Trailer | Reg. | Yr State | Removed to/by

Seat Position			Name	Address	Pos	Age	Sex	Inj
1	2	3						
4	5	6						

Total Occupants | Local Use/Owner | Injured taken to

Driver #1

Vehicle #2

State | Drivers License | DOB | Hazardous Action | HBD | HN | Test

Driver No. 2 First M. Last | Address | City | State | Age | Sex | Inj

Year | Make | Type | Trailer | Reg. | Yr State | Removed to/by

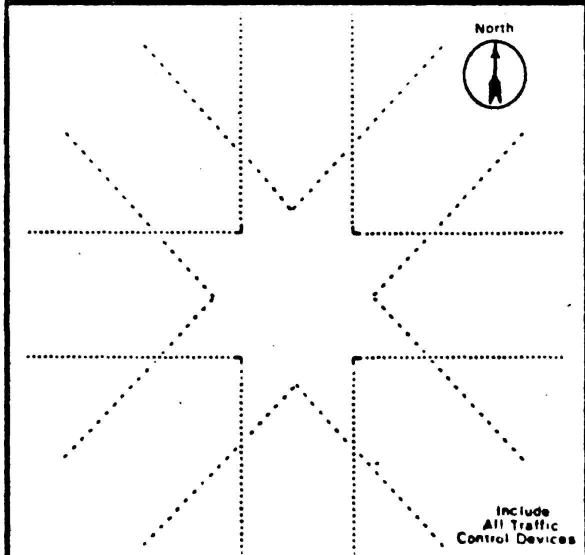
Seat Position			Name	Address	Pos	Age	Sex	Inj
1	2	3						
4	5	6						

Total Occupants | Local Use/Owner | Injured taken to

Driver #2

WEATHER	LIGHT	ROAD SURFACE	ROAD CONDITION	VISION OBSTRUCTION	VEHICLE DEFECTS
Clear / Cloudy	Day	Dry	Engineering	Vehicle #1	Vehicle #1
Rain	Dark	Snowy / Icy	Maintenance	Vehicle #2	Vehicle #2
Fog	Dawn / Dusk	Wet	Construction Zone	Explain	Explain
Snow	Street Lights	Other	Explain	None	None

Impact Severity Veh #1 | Impact Severity Veh #2 | Tot Veh | TOTAL LANES: Divided, Limited Access | DRIVER RE-EXAM.: Driver #1, Driver #2 | Damage to Property Other Than Vehicles | Owner | Address



ACCIDENT DESCRIPTION & REMARKS

Describe all unusual conditions and circumstances

Date | File | Complaint No.

Date Received | Time A.M. P.M. | Investigators | 1 2 POLICE ACTION: Cited for Hazardous Vio.; Cited for Other Violation; No Enforcement Action; Investigated at Scene | Reviewer

Photos by | Charge | Comp. Status: open, closed

FORWARD COPY TO: Michigan State Police
Safety & Traffic Division
East Lansing, Mich. 48823

This form is prescribed by Director, Michigan State Police pursuant to Section 622, Act 300, P.A. 1949, as amended.

Figure 7.2. A Police Accident Report Form from Michigan.

Second Priority:

Vehicle

Pressure in Each Tire
Tread Depth of Each Tire (Center of Pattern)
Lubrication Sticker Presence and Mileage
Indicated on Same
Inches of Steering Wheel Play

Driver

Occupation
Annual Income
Years Formal Education
Years Driving Experience
Formal Driver Education
Number of Vehicles Regularly Driven
Violations Previous Year
Accidents Previous Three Years

Road Condition

Surface Skid Resistance Qualities

A sample supplemental form is not given here since, as with the exposure collection program, a series of steps similar to those outlined in Subsection 7.2.1 should be instituted to develop a practical and efficient reporting procedure.

7.2.3 Vehicle Handling Data Collection. As discussed in Section 6, properties influencing vehicle handling can be divided into three categories, viz.:

- design parameters
- normal handling performance indices
- limit handling performance indices

In principle, it would be desirable to have a data library which contains all of the above elements for each of the models in the motor-car population. Correlation studies could then be conducted to determine which of these performance descriptors or design parameters correlate with specific kinds of accident involvements or, alternatively, hypotheses relating specific descriptors to overinvolvements in accidents could be checked for validity.

From the standpoint of trying to determine whether vehicle handling makes a significant contribution to the accident record, the existence of a complete handling data library can be considered to be an ideal state of affairs. Unfortunately, such a state of affairs does not exist and it becomes necessary to consider the implications of trying to achieve this state or achieving a lesser state as dictated by the realities of the situation. Clearly, the establishment of a data bank defining the performance characteristics and relevant design parameters of motor cars has not been a routine task pursued by the motor vehicle industry nor has it been a task that has been consistently pursued by the research community under the auspices of the Federal Department of Transportation.

Since the collection of the desired data is both time-consuming and costly, the efforts expended to date reflect either motivations and needs peculiar to the motor car design and development task or the desire of the federal government to advance its capability for defining and issuing needed motor vehicle safety standards. Further, if handling data have been obtained by the car manufacturing companies, it is frequently considered proprietary. It follows that a complete and systematic collection of vehicle performance data, as needed (in the ideal sense) to implement the proposed methodology will come into existence only if the creation of such a data bank is mandated by the government. In the interim, investigators are required to (1) adopt an ad hoc approach and (2) "scrounge" for data wherever they can find it.

With respect to the three categories of data identified earlier, we find that the current state of affairs is one in which certain design parameters (bearing on vehicle performance) are included in the passenger car specifications published by the MVMA (see Table 6.6 in Section 6). (It would appear that comparable information can also be obtained for foreign vehicles.) To a limited extent, performance indices descriptive of normal handling behavior (see Table 6.7) have been measured and published in the open literature. As already mentioned, measurements of this kind (when conducted by a manufacturer) are generally considered proprietary. However, normal handling indices (that, by definition, are open loop) are not very difficult nor expensive to obtain and their release by manufacturers seems to be inhibited more by legal and policy considerations than by technical considerations. On the other hand, the acquisition of "limit handling performance indices," (see Table 6.8) either by industry or government, is a much more demanding enterprise and requires a significant amount of dollar expenditures.

However, we do not seem to have a choice. Either all or part of these three categories of handling data must be acquired for a significant number of vehicles or the "determination of the role of vehicle handling in accident causation" becomes a meaningless phrase. As has been discussed earlier, the development of a library of handling indices (e.g., Tables 6.7 and 6.8) for upwards of 100 vehicle models should be adequate for investigating the question of interest. The testing methods and data collection procedures involved in deriving these indices have been treated elsewhere [10, 35, 37, 43, 44, 45] and thus need not be repeated here.

In choosing vehicles for the group of 100, consideration should be given to selecting vehicles that have wide diversity in cornering, braking, and acceleration characteristics, and which are as widely distributed as possible in the designated vehicle population. It is recommended that the selection process be initiated by first choosing vehicles in the order of their numbers in the designated population. Appropriate substitutions should then be made in a second step to insure a diversity of characteristics.

7.2.4 Collection of Vehicle Image Risk Data. As was discussed earlier, the reason for considering "image risk" as a factor in accident causation stems from a concern that vehicle handling performance indices, as objectively measured, may not or will not explain any finding that one vehicle is more accident prone than another. It seems likely, for example, that an individual driver may drive one vehicle one way and a different vehicle in a completely different manner. One could conjecture that a driver in a Porsche might drive faster, maintain smaller headways, and take more chances than he or she would if driving an Imperial. Further, most car enthusiasts would agree that a Porsche would be ranked higher in terms of handling performance than most large American cars. Thus, there is a danger that if accident rates are adjusted only for such factors as driver age, experience, etc., we would still obtain biased results, namely, the "better" handling performance of a particular vehicle may be submerged by the fact that that vehicle is characteristically driven in a more risky manner. Ample reason for this concern is available in the literature, e.g., Table 4.11, where it can be noted that vehicles generally considered as better handling vehicles are overinvolved in accidents.

It is proposed that image risk information be gathered by monitoring traffic patterns. For example, it is recommended that observations be made of the (1) speed, (2) gap or headway, (3) lane keeping, and (4) lane selection behavior of drivers as a function of the vehicle being driven. In proposing these four variables, we are hypothesizing that speed is directly related to risk. Further, we hypothesize that (1) the shorter the headway a driver maintains with respect to the vehicle immediately ahead, the higher the level of "image risk," (2) side-to-side movements within the lane or a passing maneuver (particularly on a two-lane, two-way road) evidences an increase in image risk, and (3) selecting the lane characterized by moderate or high speed travel (i.e., with respect to vehicles traveling on roadways with at least two lanes in one direction) constitutes evidence of a higher "image risk."

Data pertaining to these variables should ideally be collected at several different locations—freeways, state trunklines, county roads, urban arterials, etc. Further, care should be taken to avoid heavily congested areas where traffic volume significantly inhibits the free movement of individual vehicles.

Clearly, the collection of image risk data constitutes a new undertaking requiring considerable ingenuity for its implementation. A scheme that appears technically feasible involves the use of the ORBUS III System [46] which records vehicle speed, the time, and a frontal picture of the driver and vehicle, including the license plate. With this information and registration records, it is theoretically possible to identify the driver, the make, model, and model year of the vehicle, the weather conditions, the lane of the vehicle, and the placement within that lane. The passage times of successive vehicles could be interpreted to yield headway maintenance. A modification to the ORBUS System to include a side view picture at the same time the frontal view is being taken would undoubtedly aid in the vehicle identification task.

7.3 Trial Application of the Methodology

In light of the above discussion, it is obvious that no actual verification of the described analytical methods and data collection procedures can be accomplished short of implementing much of the recommended plan. Nevertheless, handling data does exist for a few vehicles, and mass accident data is available permitting us to make limited comparisons between certain handling parameters and various accident statistics. Such a study was undertaken to demonstrate, in a preliminary way, that it is possible to combine handling information with an accident data file to search for findings related to the role of handling in accident causation. Since valid exposure-to-risk data was not available, comparisons can be drawn only in terms of accident frequencies, comparable to what was done in Section 5. Consequently, in reviewing the findings presented below, the reader should be aware that the use of accident frequencies, rather than true accident rates, gives results that could be completely different if it were possible to account for exposure to risk and image risk.

7.3.1 Procedure. As indicated in Section 6.6, available vehicle parameter and performance index data were organized into an accessible computer file. Concurrently, an accident data file was constructed from accident cases from King County, Washington containing only vehicles for which parameter data was available. The accident data were further filtered along the lines discussed in Section 5.1.1 in order to restrict the final set to cases most likely to involve handling-related causation factors. The vehicle parameter data and the associated accident data were then made jointly accessible through a computer subroutine so that the frequency of accidents involving any particular vehicle parameter could be directly compared with any of several accident descriptors.

Ten accident descriptors were selected from the King County file for correlation with handling descriptors, viz.:

1. Character of Road (Straight or Curved)
2. Road Surface Condition (Wet or Dry)
3. Rollover Action
4. Skidding Action
5. An Avoidance Maneuver (Yes or No)
6. Driver Sex
7. Driver Age
8. Driver Occupation
9. Number of Vehicle Occupants
10. Character of Road and Road Surface

Interrogation of the computer files yielded numerous tables showing the relationship between selected vehicle parameters and these accident descriptors. Some of these tables show a connection between parameter values and accident frequencies; the majority do not. Again we caution that irrespective of whether an apparent connection, or lack of connection, is indicated here, it should be kept in mind that these results are preliminary and should not be considered as definitive findings.

7.3.2 Results. As discussed in Section 6, vehicle descriptors have been classified into three categories, namely, (1) design parameters (see Table 6.6), (2) normal handling performance indices (see Table 6.7), and (3) limit handling performance indices (see Table 6.8). The design data are available for all American automobiles from 1969 onward through the MVMA Specification Forms [36]. Consequently, there was more than an adequate number of accident cases with which to derive statistical comparisons. However, normal handling performance data were available for only sixty vehicles. Even so, there was generally enough variation among these sixty to show a relationship between accident experience and specific handling indices, if such a relationship exists.

Unfortunately, the same cannot be said for the other two classes of vehicle descriptors. Limit handling performance data were available only for twelve vehicles. Some of these vehicles (e.g., Lotus, Austin American, Mercedes) occur so infrequently in the domestic vehicle population as to be almost completely unrepresented in the accident statistics. Therefore, no meaningful results could be obtained, even on a demonstration basis.

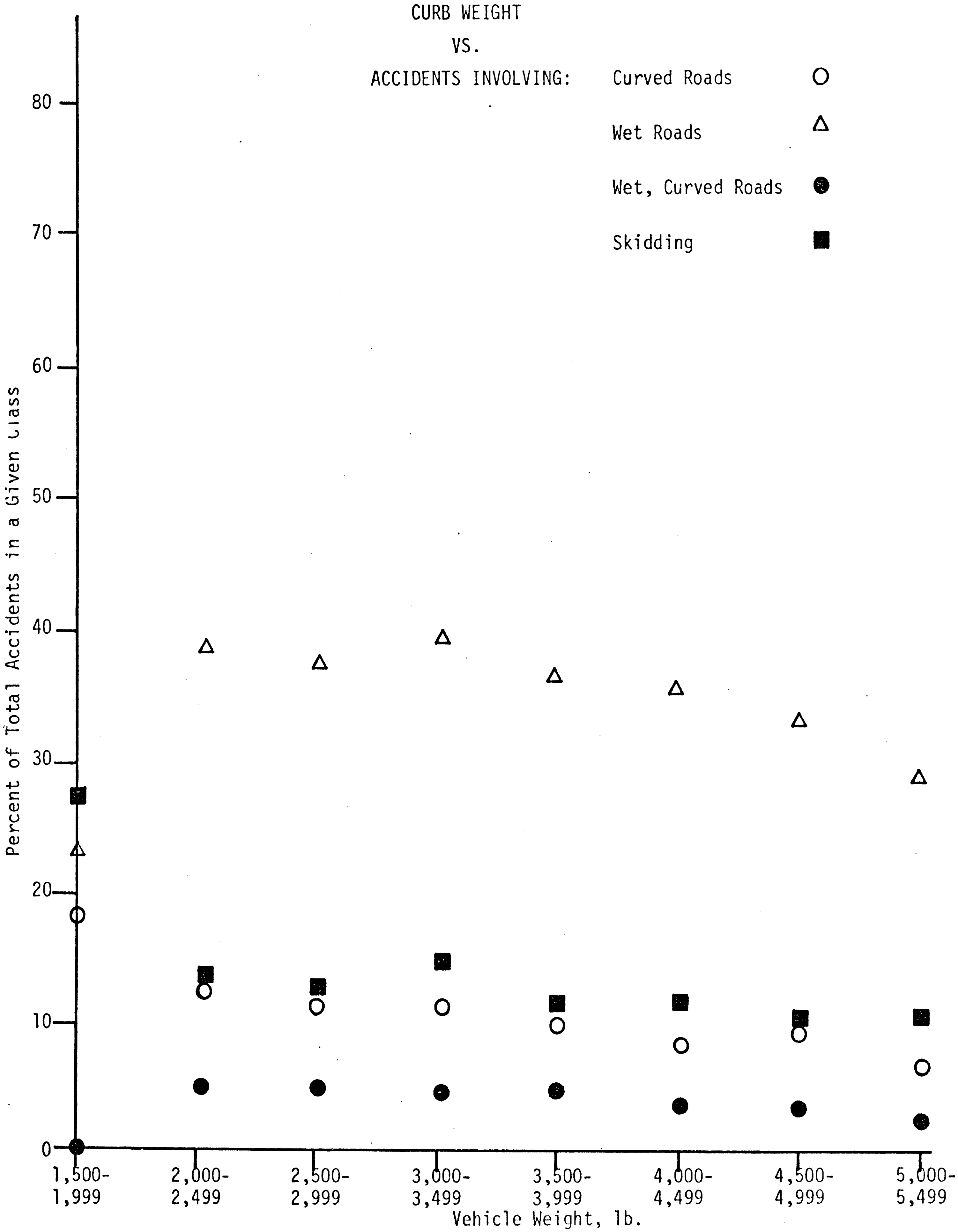
(Attempts to correlate design parameter and normal handling indices for vehicle loading, as per Table 6.9, were generally unsuccessful. A technique was developed for predicting vehicle loading by estimating the weight of vehicle occupants, since the actual weights of occupants was not available. The estimating process involved taking the age and sex of the occupant and assigning a corresponding median weight as determined from population surveys. The attempt was not successful, however, in that parameter adjustments for occupant loading produced no noticeable improvements in correlations with accident frequencies.)

In the discussion that follow, we, therefore, consider only the relationship of design parameters and normal handling performance indices to accident descriptors. Each of the parameters and indices which show some relationship to the accident descriptors are discussed in turn.

Of the design parameters examined, four are (more or less) related to vehicle size, namely, curb weight, overall length, wheelbase, and track. Each of these variables were found to exhibit a consistent relationship to accident frequencies. Comparisons of accident frequencies in terms of the various accident descriptors as a function of these parameters are given in Figures 7.3 through 7.10. (The statistics shown represent that percentage of accidents of a particular type as compared to the total number of accidents occurring for vehicles with a particular vehicle parameter value.) Accidents occurring on curves, under wet conditions, on curves under wet conditions, and those involving skidding are shown on Figures 7.3 to 7.6. Accidents involving rollover, avoidance maneuvers, female drivers, and vehicles with more than one occupant are shown on Figures 7.7 to 7.10.

In examining Figures 7.3 to 7.6, it is evident that there is a consistent trend toward fewer accidents as curb weight and wheelbase increase in value. Accidents as a function of overall length tend to peak at lengths associated with compact cars. Accident trends associated with track width are less consistent. Accidents on curves show a general downward trend as track width increases while wet weather accidents tend to peak at track widths between 54 and 58 inches. Skidding accidents and accidents on curves in wet weather are essentially independent of track width.

The most consistent trend in Figures 7.7 to 7.10 is that of rollover accidents. Rollover accidents consistently decrease with increasing values of all four vehicle size variables. Accidents involving avoidance maneuvers tend to peak again at parameter values associated with compact cars. Accidents involving female drivers show no consistent trends except in the case of overall length where a distinct downward trend is evident. No consistent trends are apparent for accidents involving more than one vehicle occupant.



CURB WEIGHT
VS.
ACCIDENTS INVOLVING:
Curved Roads
Wet Roads
Wet, Curved Roads
Skidding
Percent of Total Accidents in a Given Class
80
70
60
50
40
30
20
10
0
1,500-
1,999
2,000-
2,499
2,500-
2,999
3,000-
3,499
3,500-
3,999
4,000-
4,499
4,500-
4,999
5,000-
5,499
Vehicle Weight, lb.

Figure 7.3

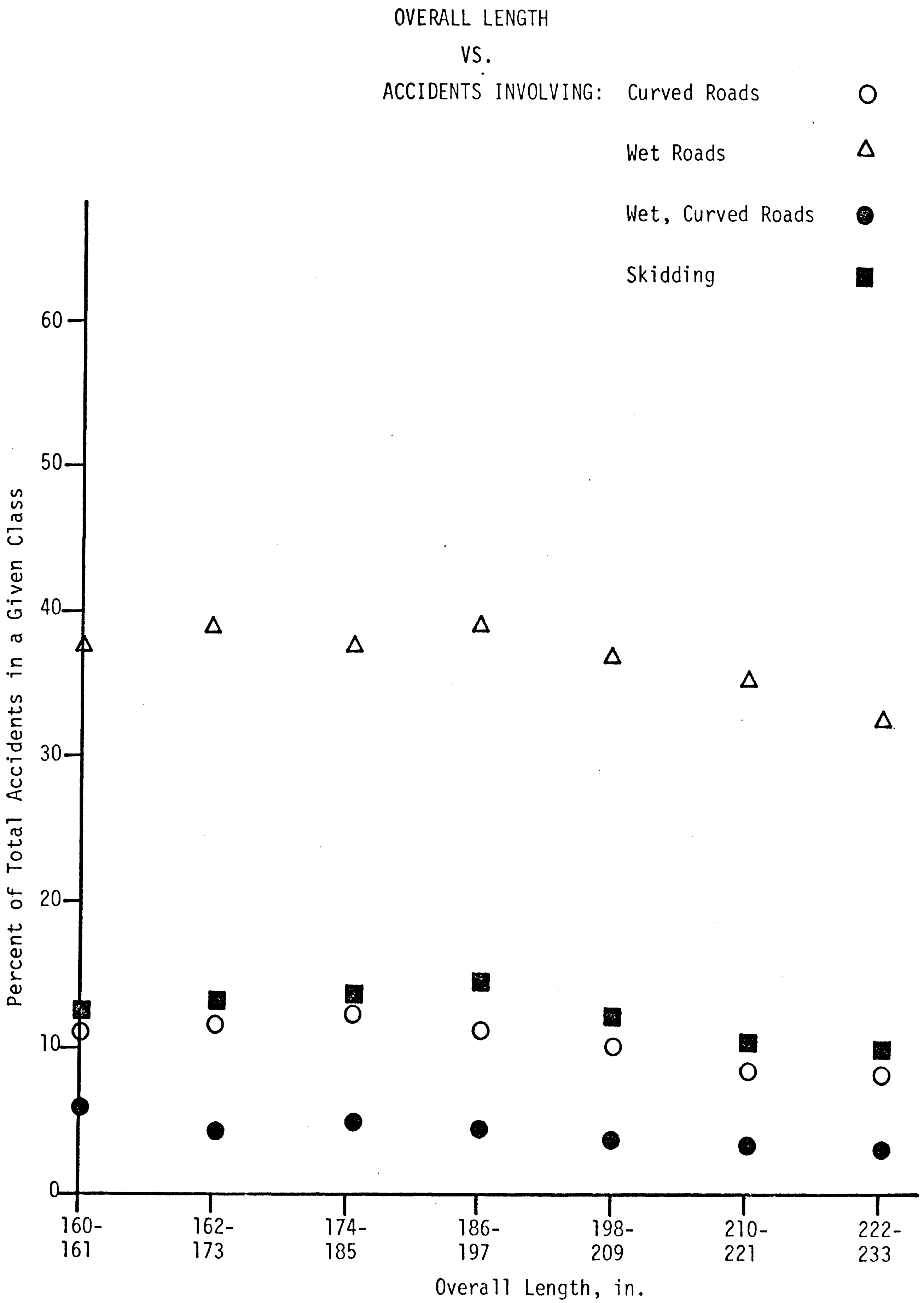

OVERALL LENGTH
VS.
ACCIDENTS INVOLVING: Curved Roads
Wet Roads
Wet, Curved Roads
Skidding
Percent of Total Accidents in a Given Class
60
50
40
30
20
10
0
160-161
162-173
174-185
186-197
198-209
210-221
222-233
Overall Length, in.

Figure 7.4

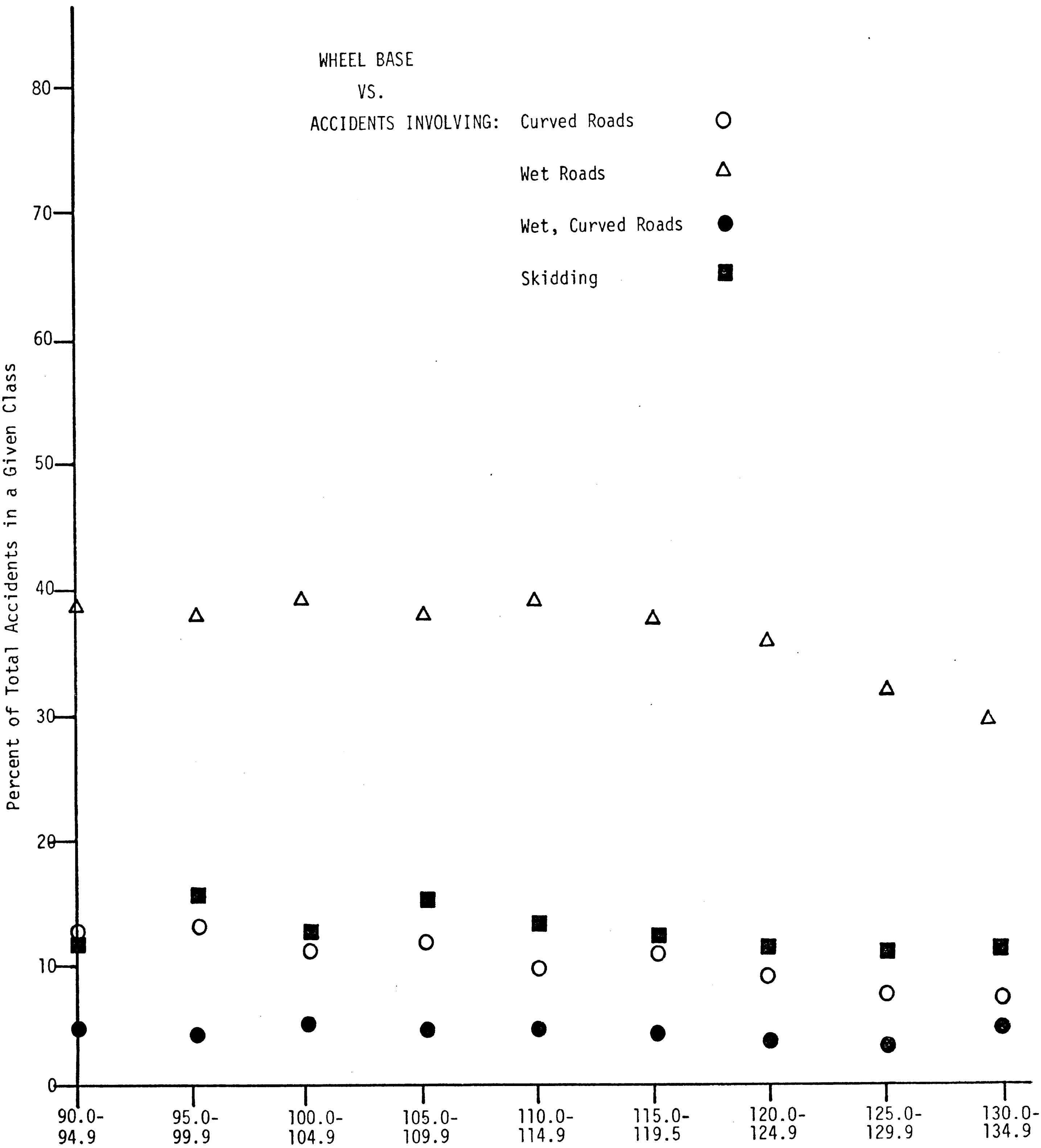

WHEEL BASE
VS.
ACCIDENTS INVOLVING: Curved Roads
Wet Roads
Wet, Curved Roads
Skidding
80
70
60
50
40
30
20
10
0
Percent of Total Accidents in a Given Class
90.0-94.9
95.0-99.9
100.0-104.9
105.0-109.9
110.0-114.9
115.0-119.5
120.0-124.9
125.0-129.9
130.0-134.9
Wheel Base, in.

Figure 7.5

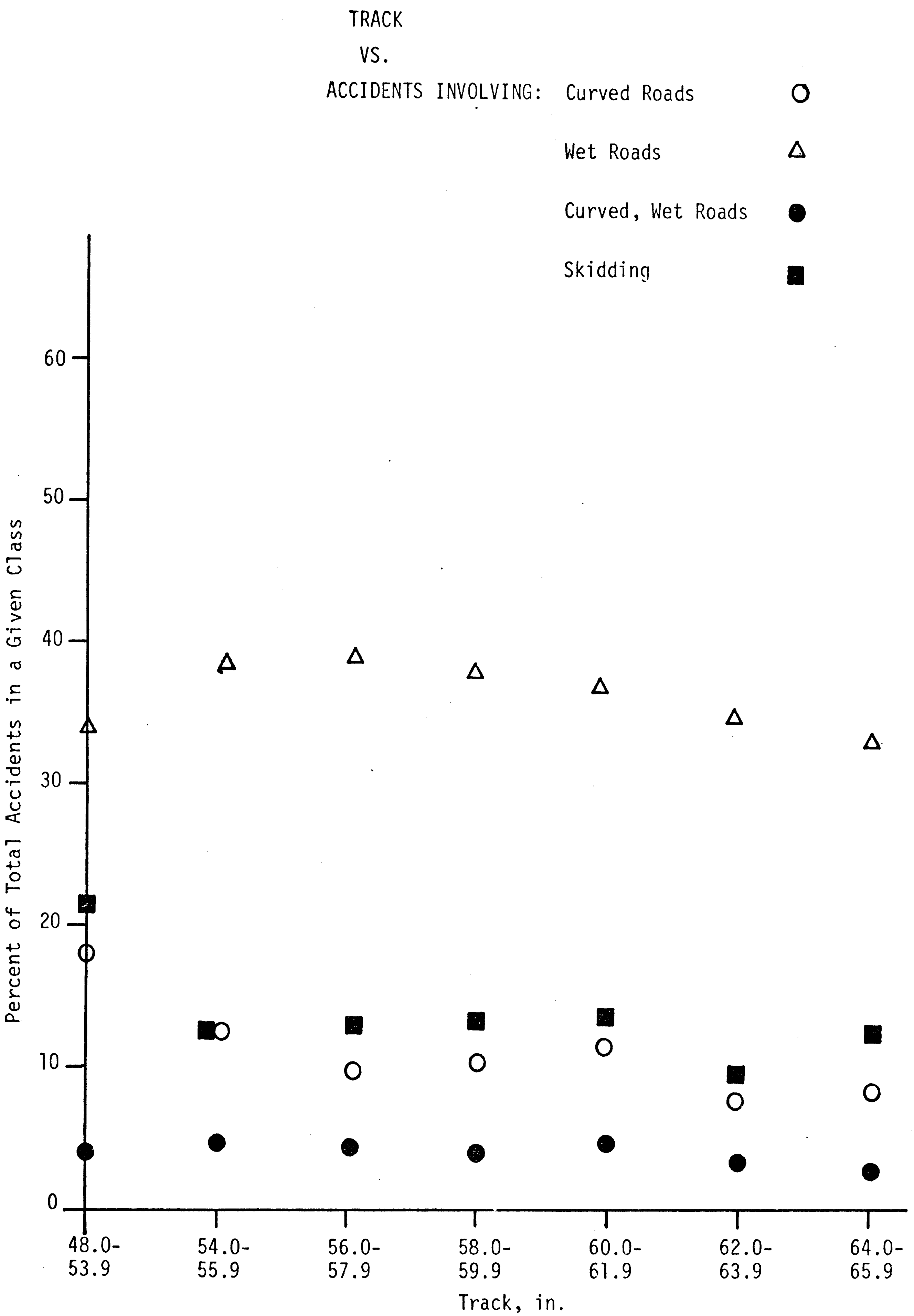

TRACK
VS.
ACCIDENTS INVOLVING: Curved Roads
Wet Roads
Curved, Wet Roads
Skidding
Percent of Total Accidents in a Given Class
60
50
40
30
20
10
0
48.0-53.9
54.0-55.9
56.0-57.9
58.0-59.9
60.0-61.9
62.0-63.9
64.0-65.9
Track, in.

Figure 7.6

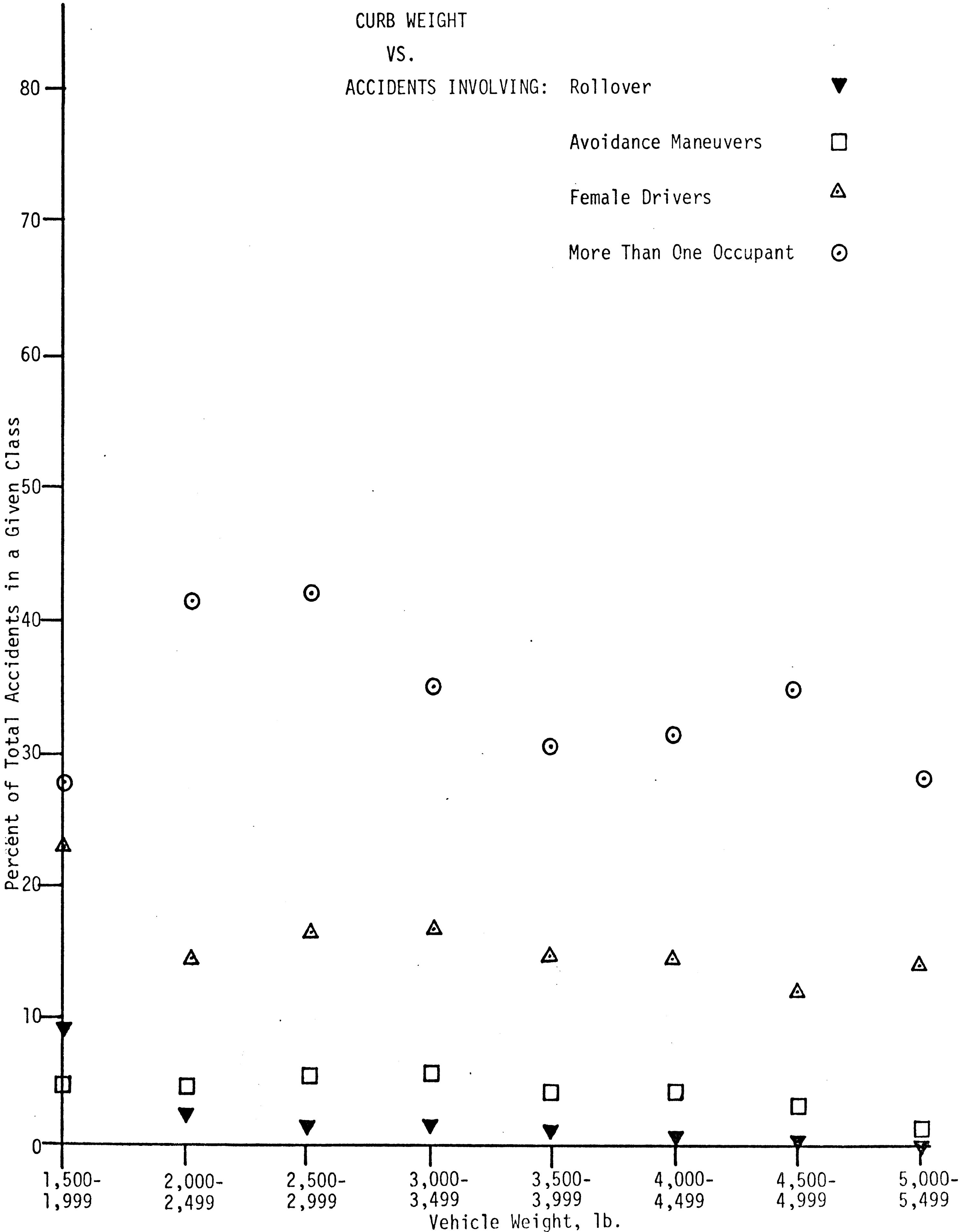

CURB WEIGHT
VS.
ACCIDENTS INVOLVING: Rollover
Avoidance Maneuvers
Female Drivers
More Than One Occupant
Percent of Total Accidents in a Given Class
80
70
60
50
40
30
20
10
0
1,500-
1,999
2,000-
2,499
2,500-
2,999
3,000-
3,499
3,500-
3,999
4,000-
4,499
4,500-
4,999
5,000-
5,499
Vehicle Weight, lb.

Figure 7.7

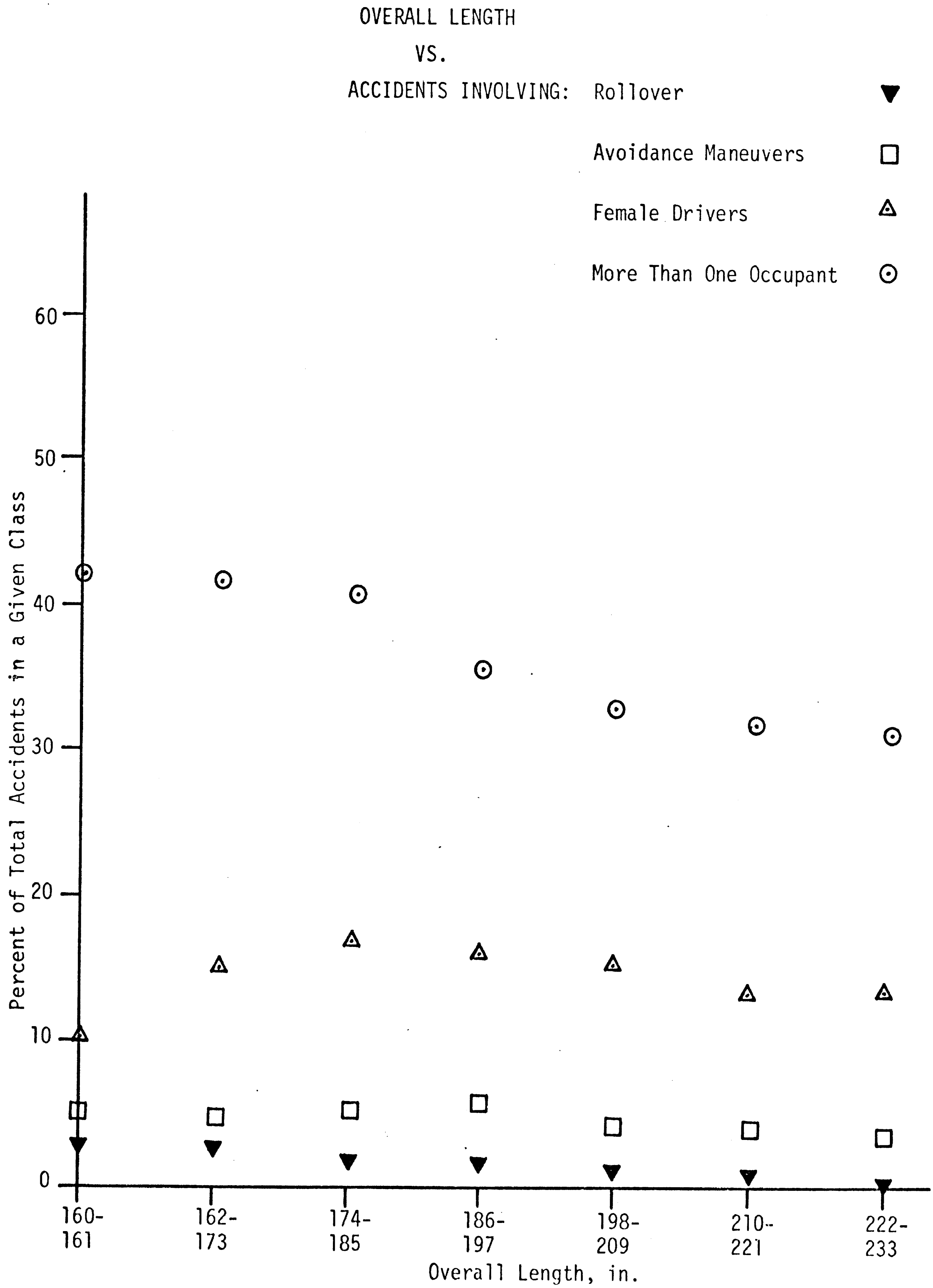

OVERALL LENGTH
VS.
ACCIDENTS INVOLVING: Rollover
Avoidance Maneuvers
Female Drivers
More Than One Occupant
Percent of Total Accidents in a Given Class
60
50
40
30
20
10
0
160-161
162-173
174-185
186-197
198-209
210-221
222-233
Overall Length, in.

Figure 7.8

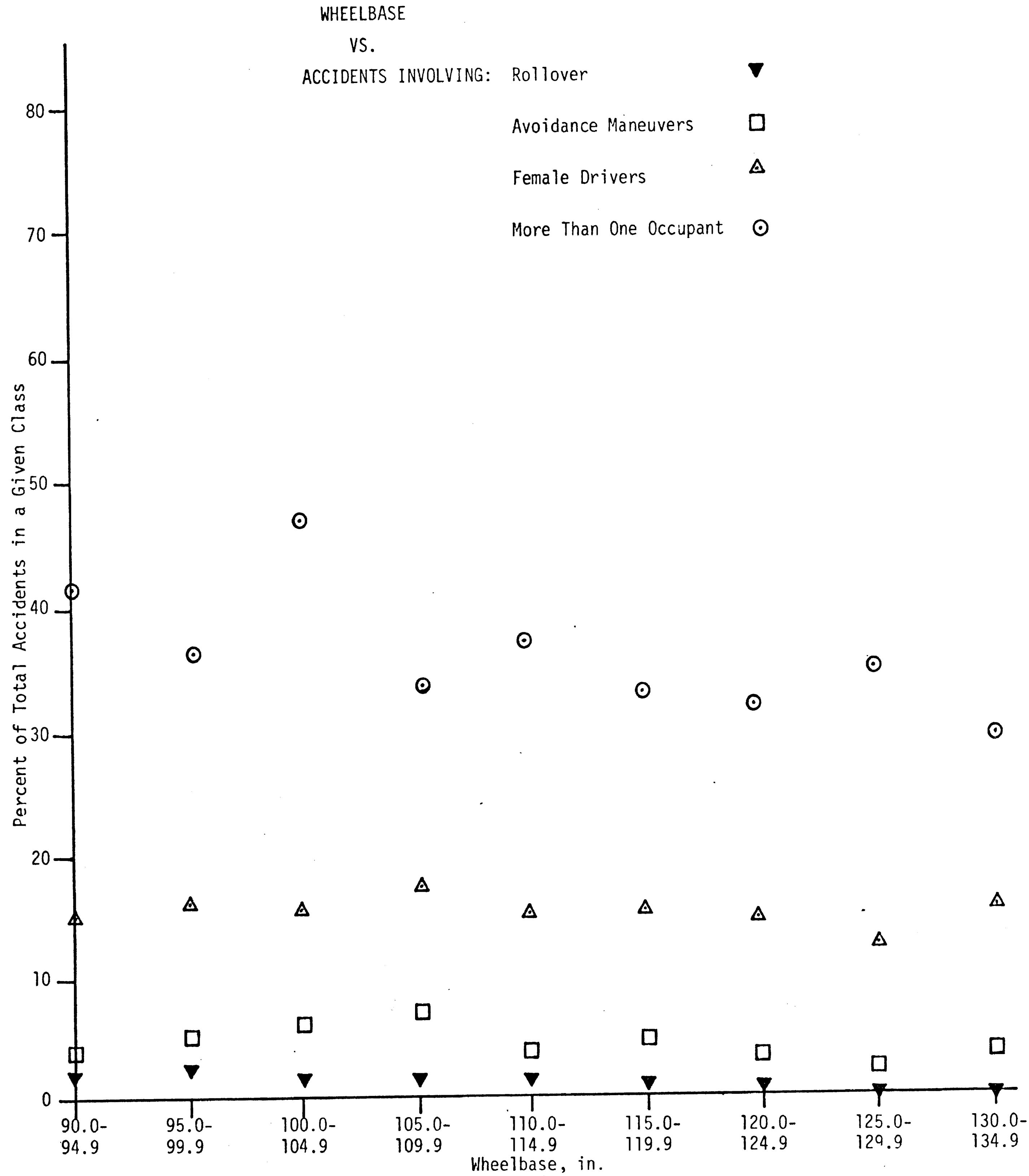

WHEELBASE
VS.
ACCIDENTS INVOLVING: Rollover
Avoidance Maneuvers
Female Drivers
More Than One Occupant
Percent of Total Accidents in a Given Class
80
70
60
50
40
30
20
10
0
90.0-94.9
95.0-99.9
100.0-104.9
105.0-109.9
110.0-114.9
115.0-119.9
120.0-124.9
125.0-129.9
130.0-134.9
Wheelbase, in.

Figure 7.9

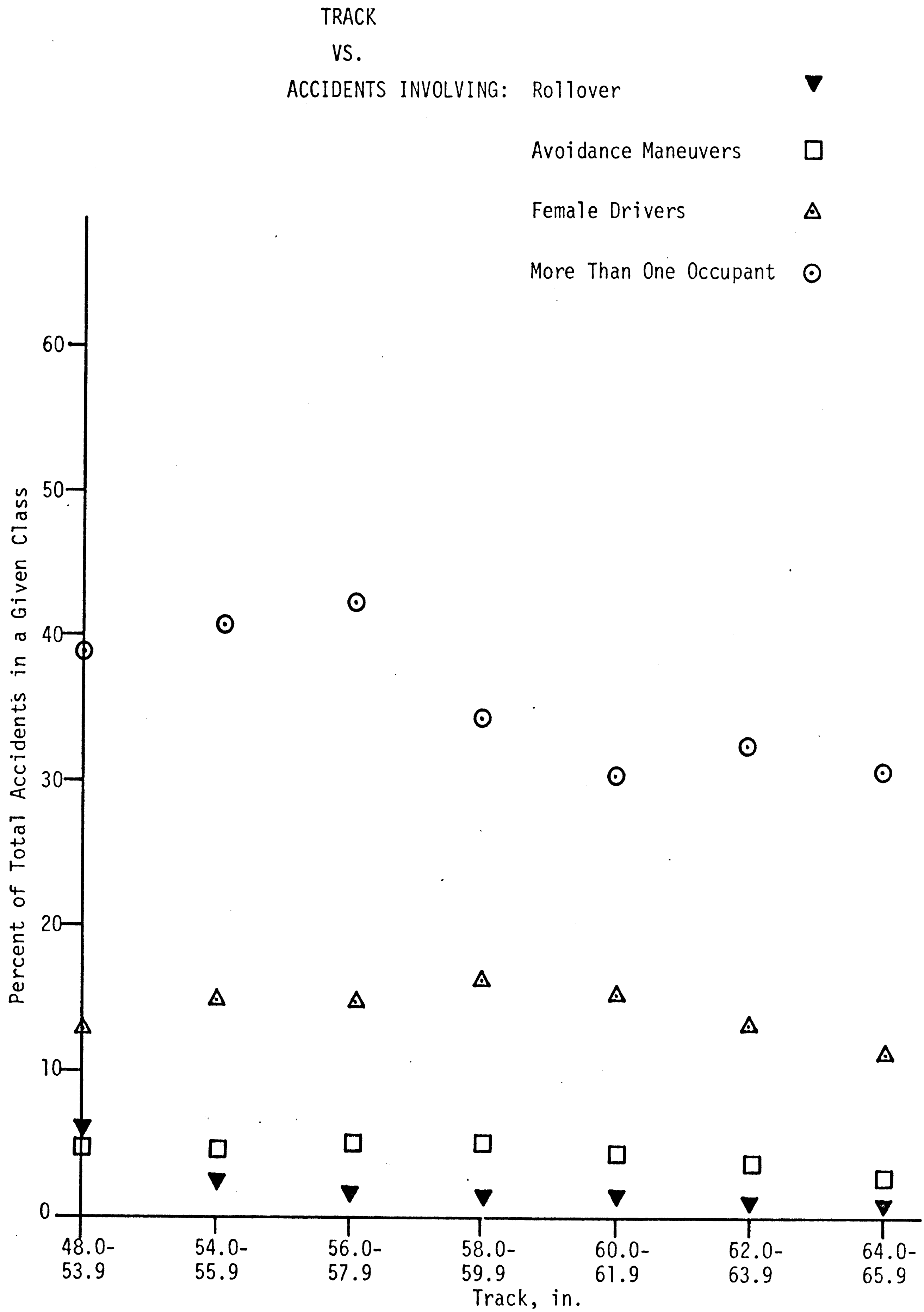

TRACK
VS.
ACCIDENTS INVOLVING: Rollover
Avoidance Maneuvers
Female Drivers
More Than One Occupant
Percent of Total Accidents in a Given Class
60
50
40
30
20
10
0
48.0-
53.9
54.0-
55.9
56.0-
57.9
58.0-
59.9
60.0-
61.9
62.0-
63.9
64.0-
65.9
Track, in.

Figure 7.10

Of the twenty-six normal handling performance indices listed in Table 6.7, the following six show a consistent relationship with at least one accident descriptor:

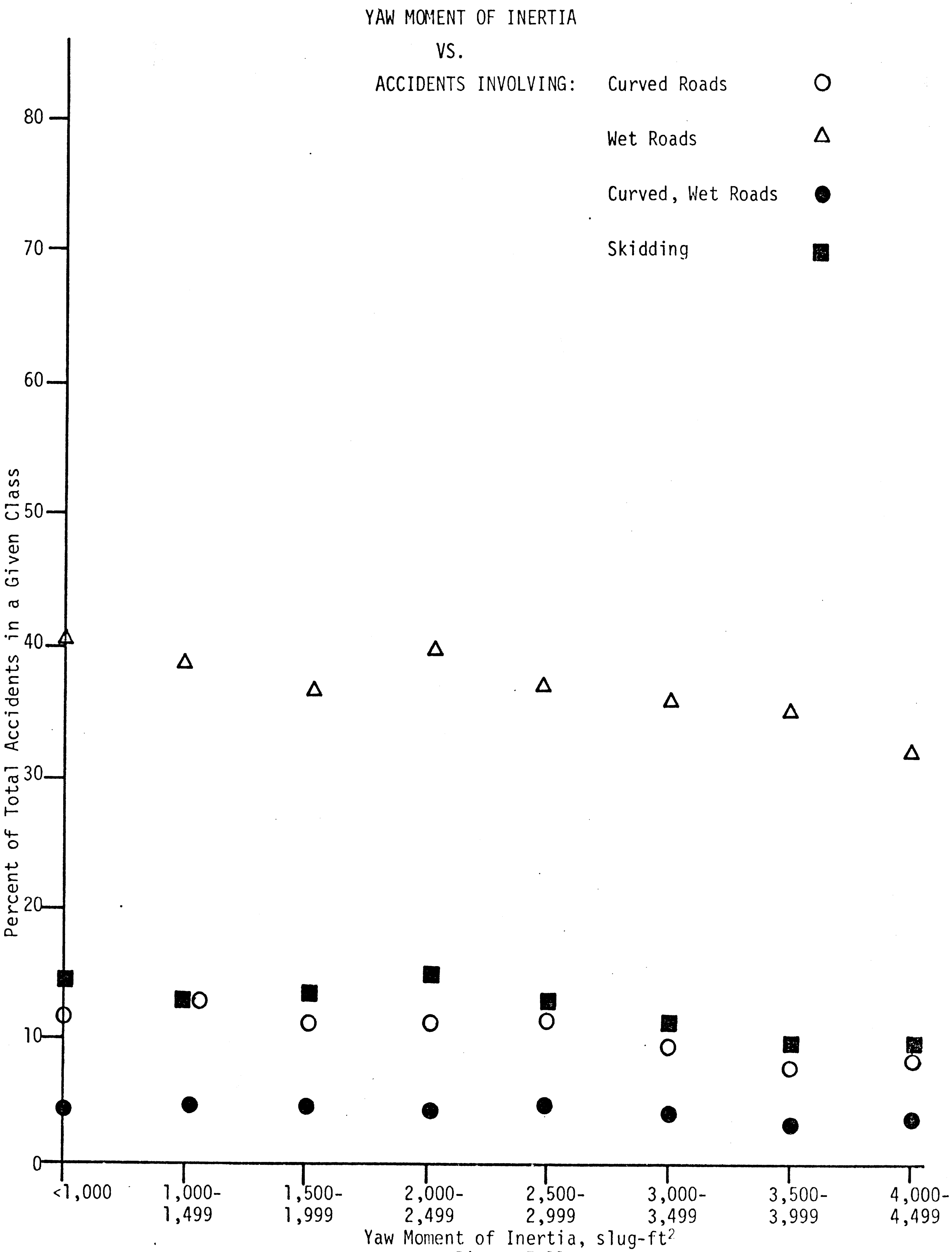
1. Yaw Moment of Inertia
2. Steering Sensitivity
3. Horsepower-to-Weight Ratio
4. Rollover Potential
5. Wind Disturbance Potential
6. Brake Torque Distribution

Accident frequencies in all classes tend to decrease as yaw moment of inertia increased beyond values of 1,500 slug-ft.^{2} (Figures 7.11 and 7.12). This finding is very likely the result of the fact that yaw moment of inertia is closely correlated with vehicle size and weight.

For steering sensitivity there is a general increase in accident frequencies for values greater than 0.5 g/100° steering wheel deflection (Figures 7.13 and 7.14). The trend is not all that consistent, however, except for accidents occurring on curves.

Accident frequencies as a function of horsepower-to-weight ratio are shown on Figures 7.15 and 7.16. Accident frequencies of all types tend to become less for horsepower-to-weight ratio greater than 0.05. This finding is again size related in that larger vehicles have higher horsepower-to-weight ratios than smaller ones. (Vehicles vary in weight by a factor of two or three, while engines vary in horsepower by factors of between eight and ten.)

Accident frequencies as a function of rollover potential are shown on Figures 7.17 and 7.18. Obviously, the primary question is whether this parameter is related to the occurrence of rollover accidents. (Rollover potential is defined here to be a dimension from the ground to the centroid of the projected side area divided by the track width.) In this regard, it is


YAW MOMENT OF INERTIA
VS.
ACCIDENTS INVOLVING:
Curved Roads
Wet Roads
Curved, Wet Roads
Skidding
Percent of Total Accidents in a Given Class
0
10
20
30
40
50
60
70
80
<1,000
1,000-1,499
1,500-1,999
2,000-2,499
2,500-2,999
3,000-3,499
3,500-3,999
4,000-4,499
Yaw Moment of Inertia, slug-ft²
Figure 7.11

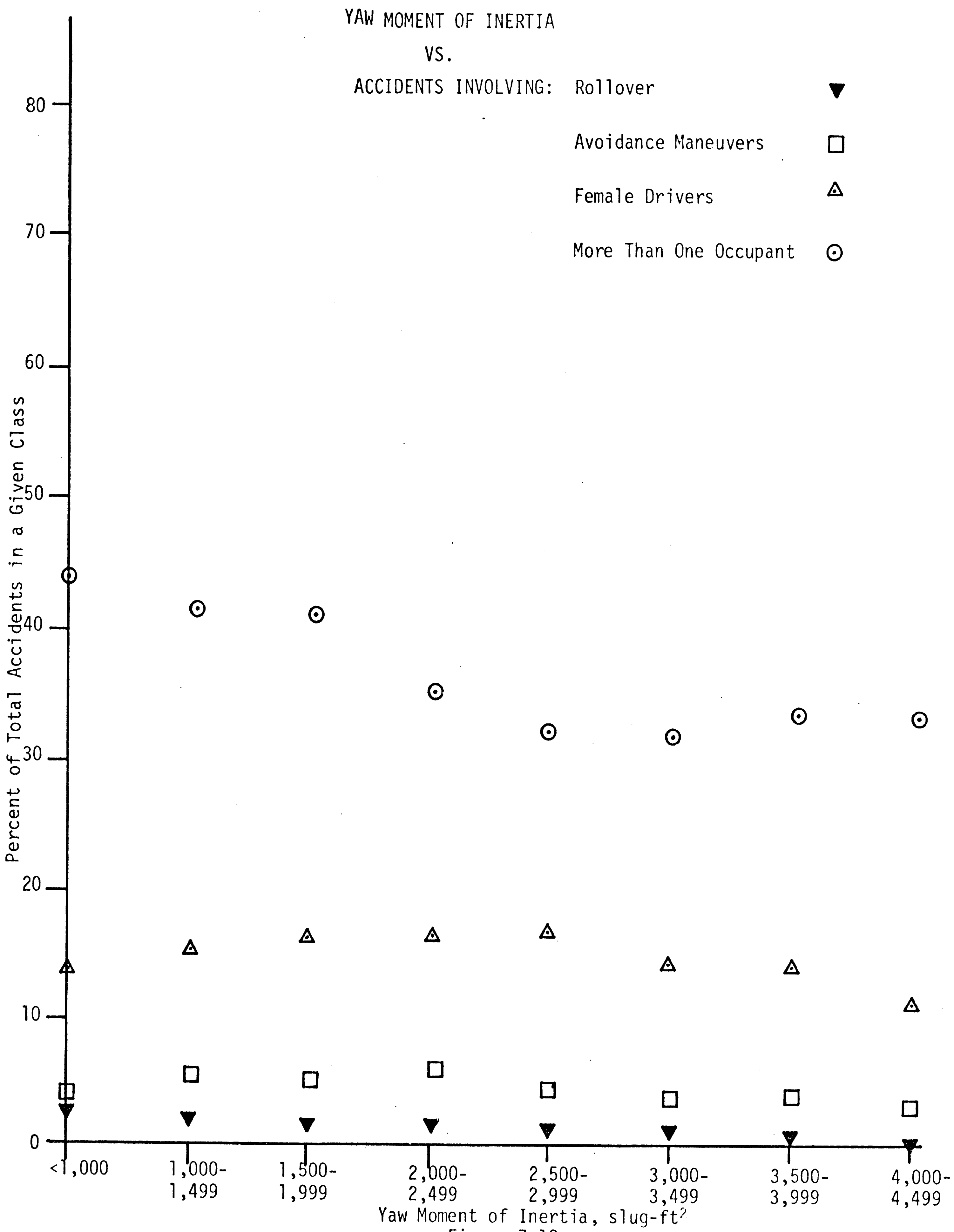

YAW MOMENT OF INERTIA
VS.
ACCIDENTS INVOLVING: Rollover
Avoidance Maneuvers
Female Drivers
More Than One Occupant
Percent of Total Accidents in a Given Class
0
10
20
30
40
50
60
70
80
<1,000
1,000-
1,499
1,500-
1,999
2,000-
2,499
2,500-
2,999
3,000-
3,499
3,500-
3,999
4,000-
4,499
Yaw Moment of Inertia, slug-ft²

Figure 7.12

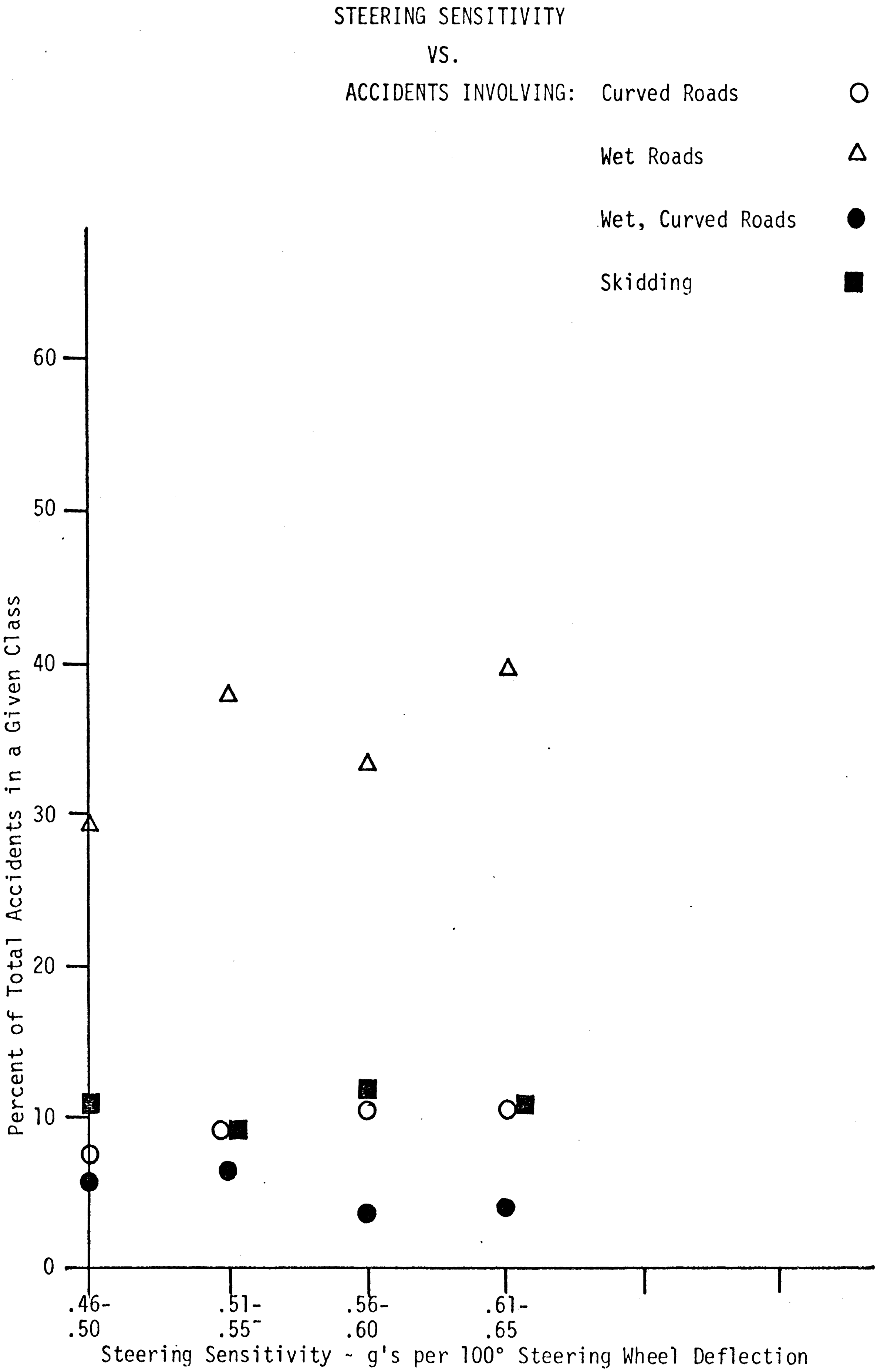
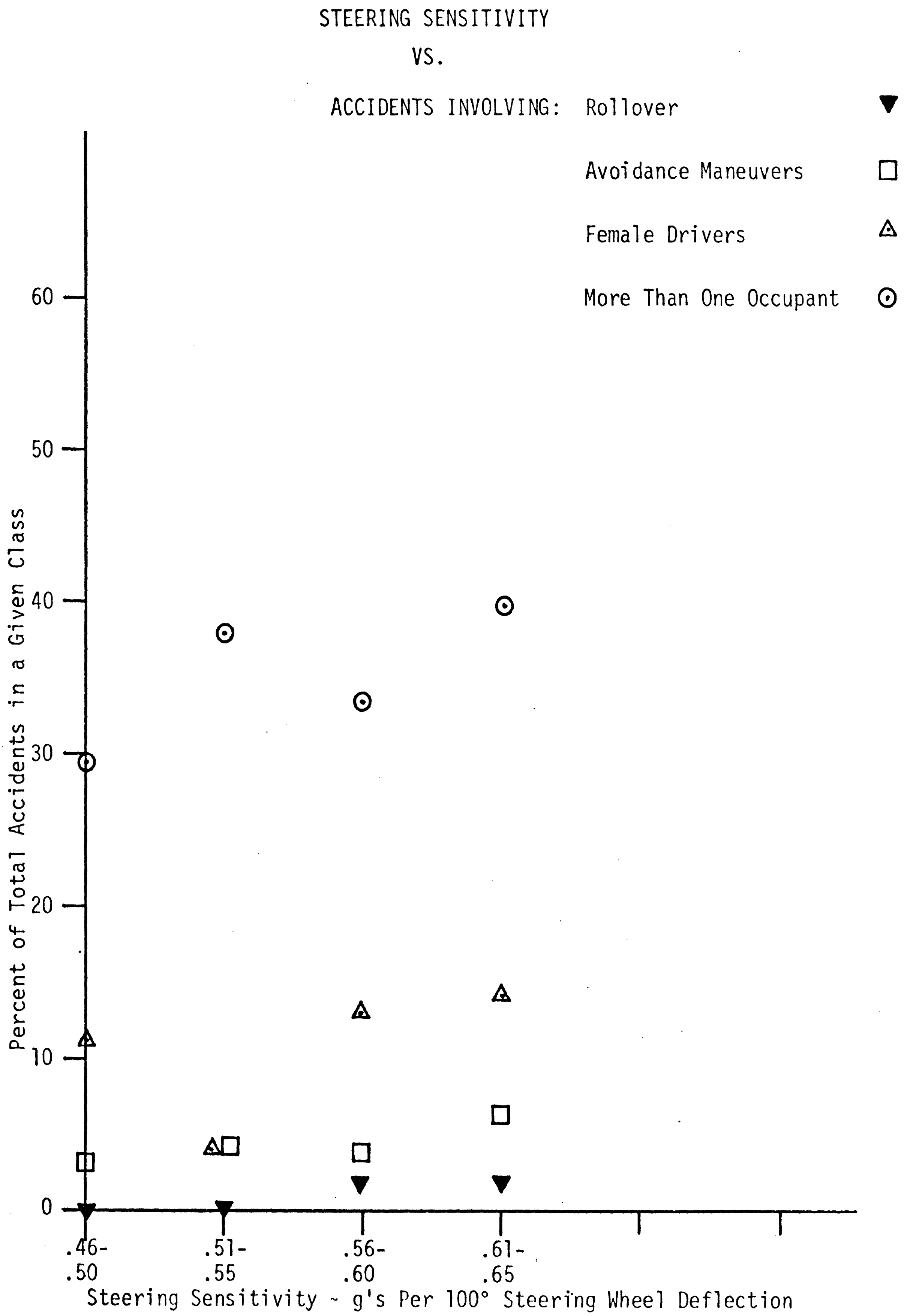

STEERING SENSITIVITY
VS.
ACCIDENTS INVOLVING: Curved Roads
Wet Roads
Wet, Curved Roads
Skidding
Percent of Total Accidents in a Given Class
60
50
40
30
20
10
0
.46-
.50
.51-
.55
.56-
.60
.61-
.65
Steering Sensitivity ~ g's per 100° Steering Wheel Deflection

Figure 7.13



STEERING SENSITIVITY
VS.
ACCIDENTS INVOLVING: Rollover
Avoidance Maneuvers
Female Drivers
More Than One Occupant
Percent of Total Accidents in a Given Class
60
50
40
30
20
10
0
.46-
.50
.51-
.55
.56-
.60
.61-
.65
Steering Sensitivity ~ g's Per 100° Steering Wheel Deflection

Figure 7.14

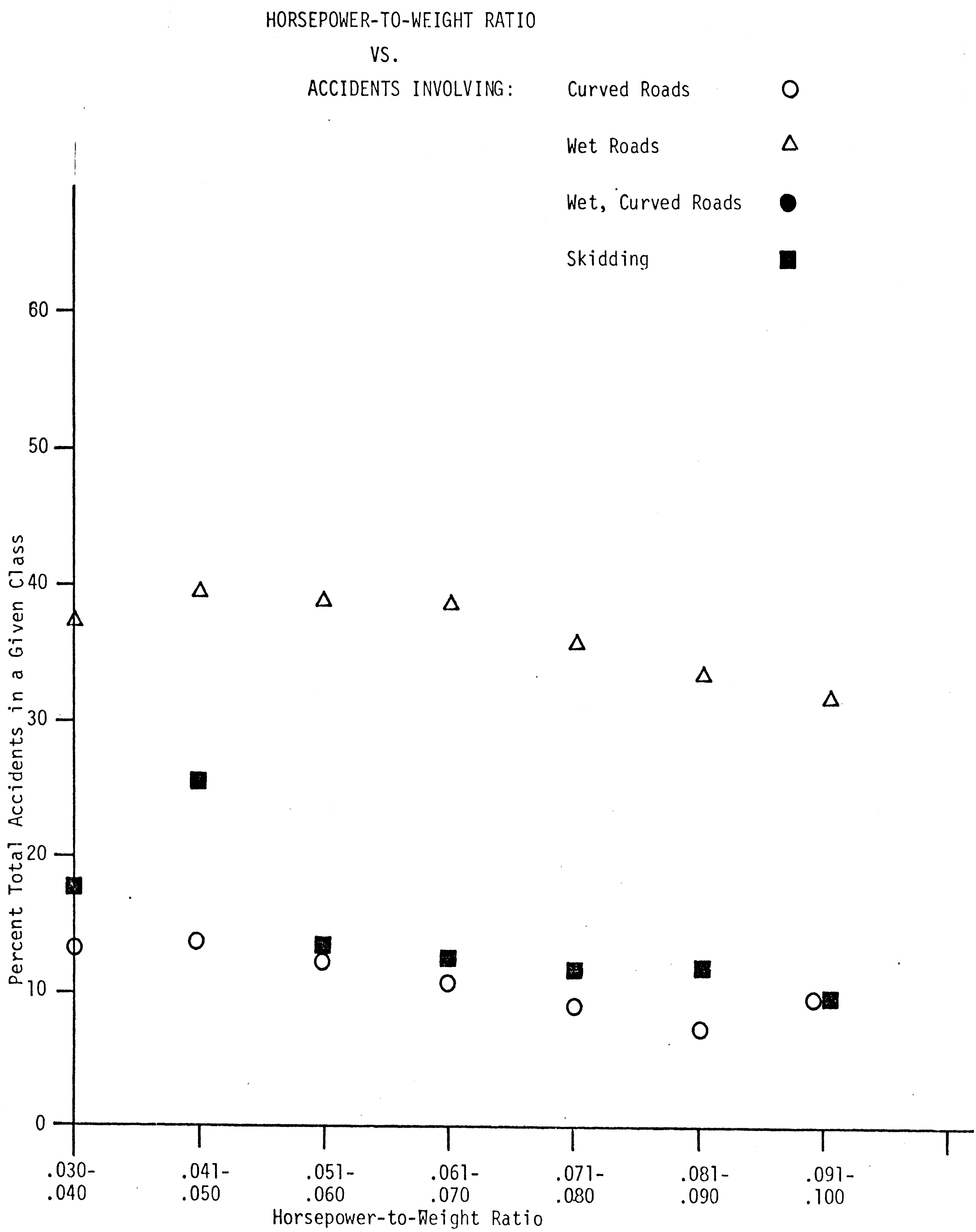

HORSEPOWER-TO-WEIGHT RATIO
VS.
ACCIDENTS INVOLVING:
Curved Roads
Wet Roads
Wet, Curved Roads
Skidding
Percent Total Accidents in a Given Class
60
50
40
30
20
10
0
.030-
.040
.041-
.050
.051-
.060
.061-
.070
.071-
.080
.081-
.090
.091-
.100
Horsepower-to-Weight Ratio

Figure 7.15

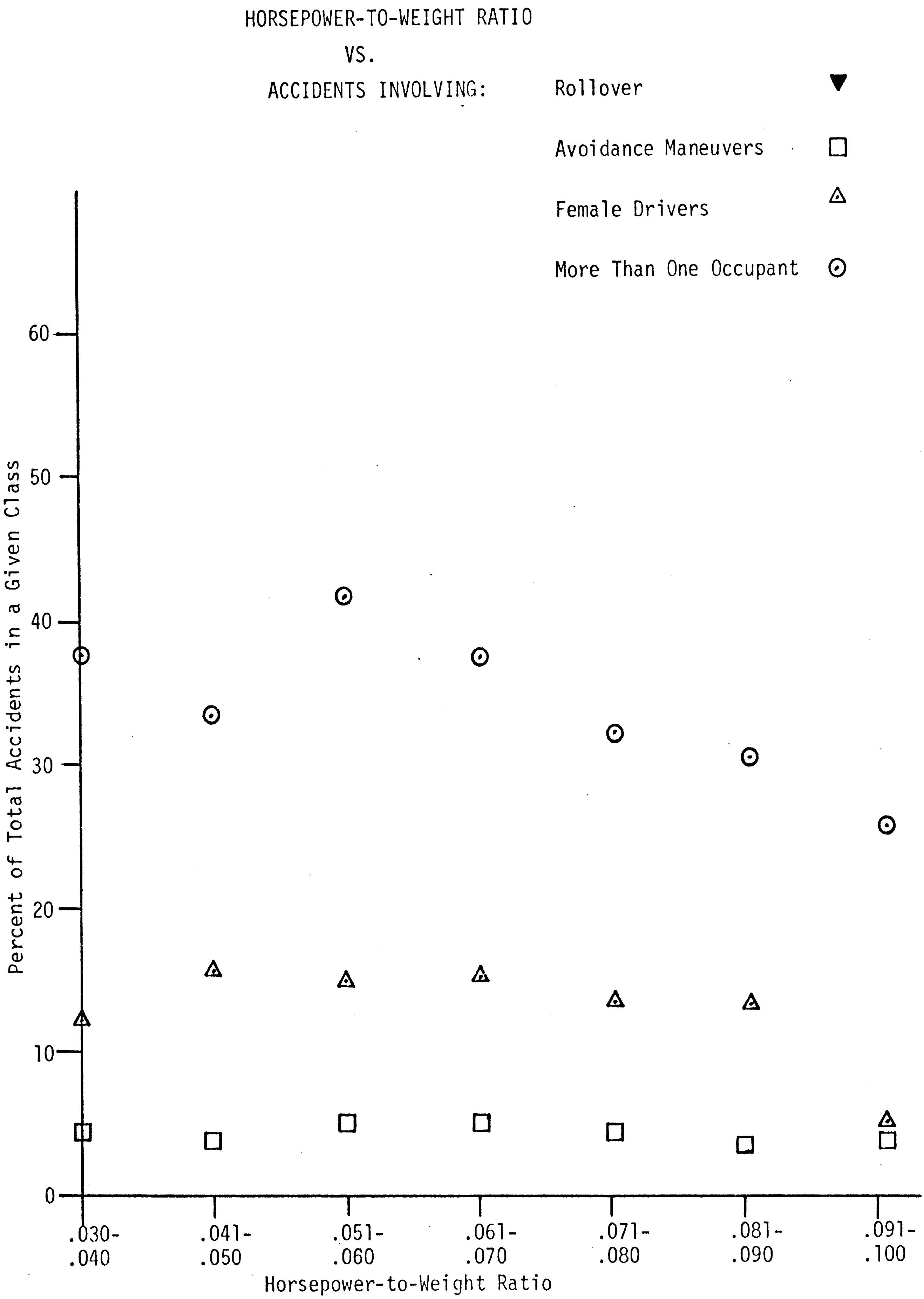
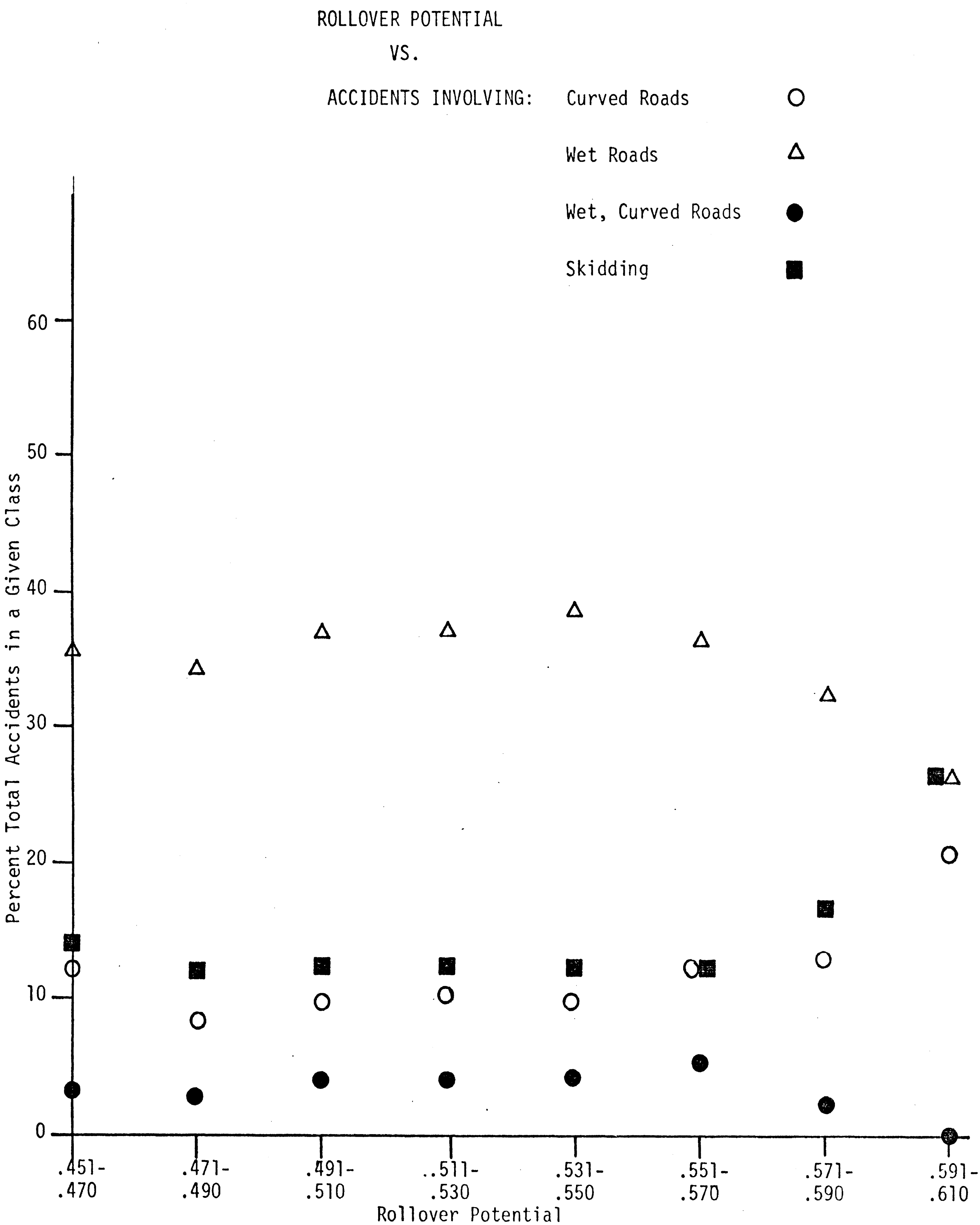

HORSEPOWER-TO-WEIGHT RATIO
VS.
ACCIDENTS INVOLVING:
Rollover
Avoidance Maneuvers
Female Drivers
More Than One Occupant
Percent of Total Accidents in a Given Class
60
50
40
30
20
10
0
.030-
.040
.041-
.050
.051-
.060
.061-
.070
.071-
.080
.081-
.090
.091-
.100
Horsepower-to-Weight Ratio

Figure 7.16



ROLLOVER POTENTIAL
VS.
ACCIDENTS INVOLVING:
Curved Roads
Wet Roads
Wet, Curved Roads
Skidding
Percent Total Accidents in a Given Class
60
50
40
30
20
10
0
.451-
.470
.471-
.490
.491-
.510
..511-
.530
.531-
.550
.551-
.570
.571-
.590
.591-
.610
Rollover Potential

Figure 7.17

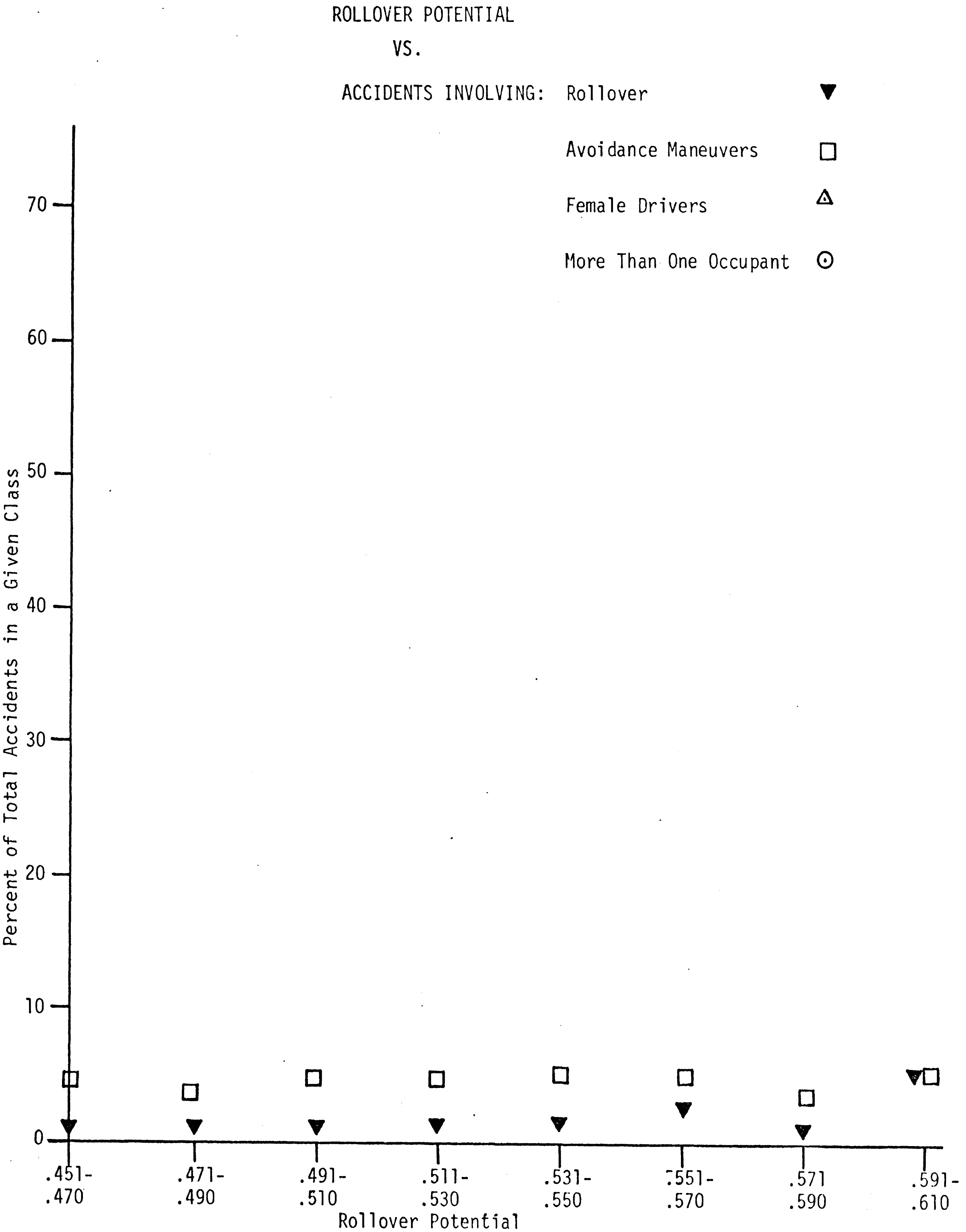

ROLLOVER POTENTIAL
VS.
ACCIDENTS INVOLVING: Rollover
Avoidance Maneuvers
Female Drivers
More Than One Occupant
Percent of Total Accidents in a Given Class
70
60
50
40
30
20
10
0
.451-
.470
.471-
.490
.491-
.510
.511-
.530
.531-
.550
.551-
.570
.571
.590
.591-
.610
Rollover Potential

Figure 7.18

obvious that rollover accidents do tend to increase with increasing values of rollover potential. The trend is not monotonically upward, however. Comparison with Figure 7.10 shows that track width, alone, tends to correlate better with rollover accidents than does the rollover potential parameter. A better predictor of rollover accidents than either of these might well be the ratio of center-of-gravity height to track width. Since c.g. heights vary by no more than two or three inches for the entire spectrum of passenger cars, however, it could be that track width is as good as any more elaborate definition for defining rollover potential. (The reason c.g. height was not included in the present study is due to the fact that such information is not available for most passenger cars.)

The variation of accident frequencies with wind disturbance potential is shown on Figures 7.19 and 7.20. Wind disturbance potential is defined to be the ratio of side area to weight. It is evident that accidents involving road curvature and wet weather increase with increasing values of the wind-disturbance-potential parameter. There is again a vehicle size factor at work here in that as vehicle weights increase, the side area increases at a lower rate than does the weight. Thus, the lower values of side area to weight ratio are associated with the larger automobiles. On the other hand, accidents on wet roads, curves, and wet curves appear to be better correlated with the wind disturbance potential parameter than with any other size-related parameter (e.g., curb weight, wheelbase, and overall length).

Figures 7.21 and 7.22 show accident frequencies as a function of brake torque distribution, i.e., the ratio of the proportion of braking on the front wheels to the proportion of weight on the front wheels. The findings are generally unremarkable except for those associated with accidents on curves and on wet curves. The former shows a general upward trend with increasing distribution of brake proportioning to the front wheels. The upward trend for accidents on wet curves is even stronger. These results are interesting since the question of how to properly

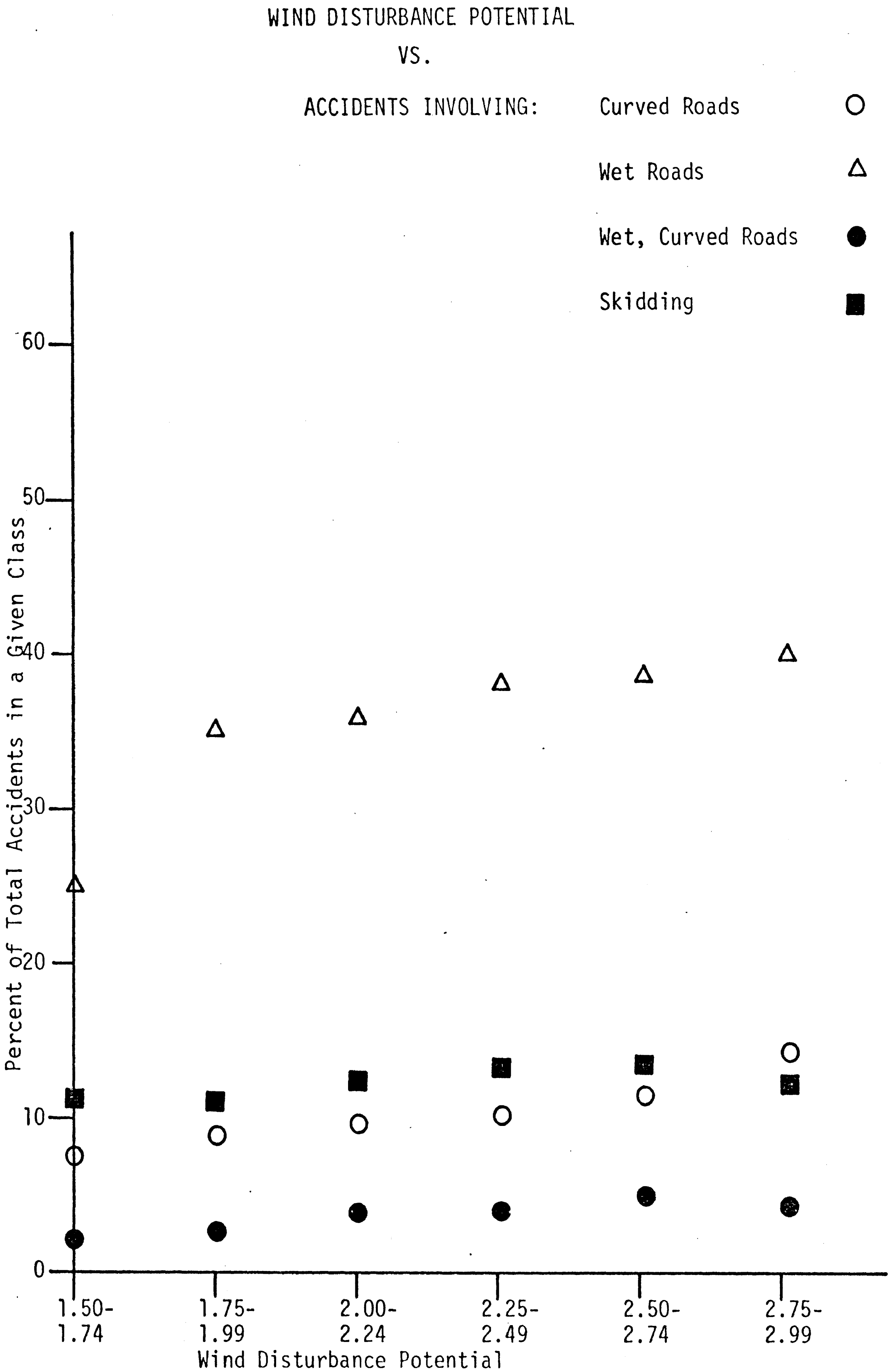

WIND DISTURBANCE POTENTIAL
VS.
ACCIDENTS INVOLVING:
Curved Roads
Wet Roads
Wet, Curved Roads
Skidding
Percent of Total Accidents in a Given Class
60
50
40
30
20
10
0
1.50-
1.74
1.75-
1.99
2.00-
2.24
2.25-
2.49
2.50-
2.74
2.75-
2.99
Wind Disturbance Potential

Figure 7.19

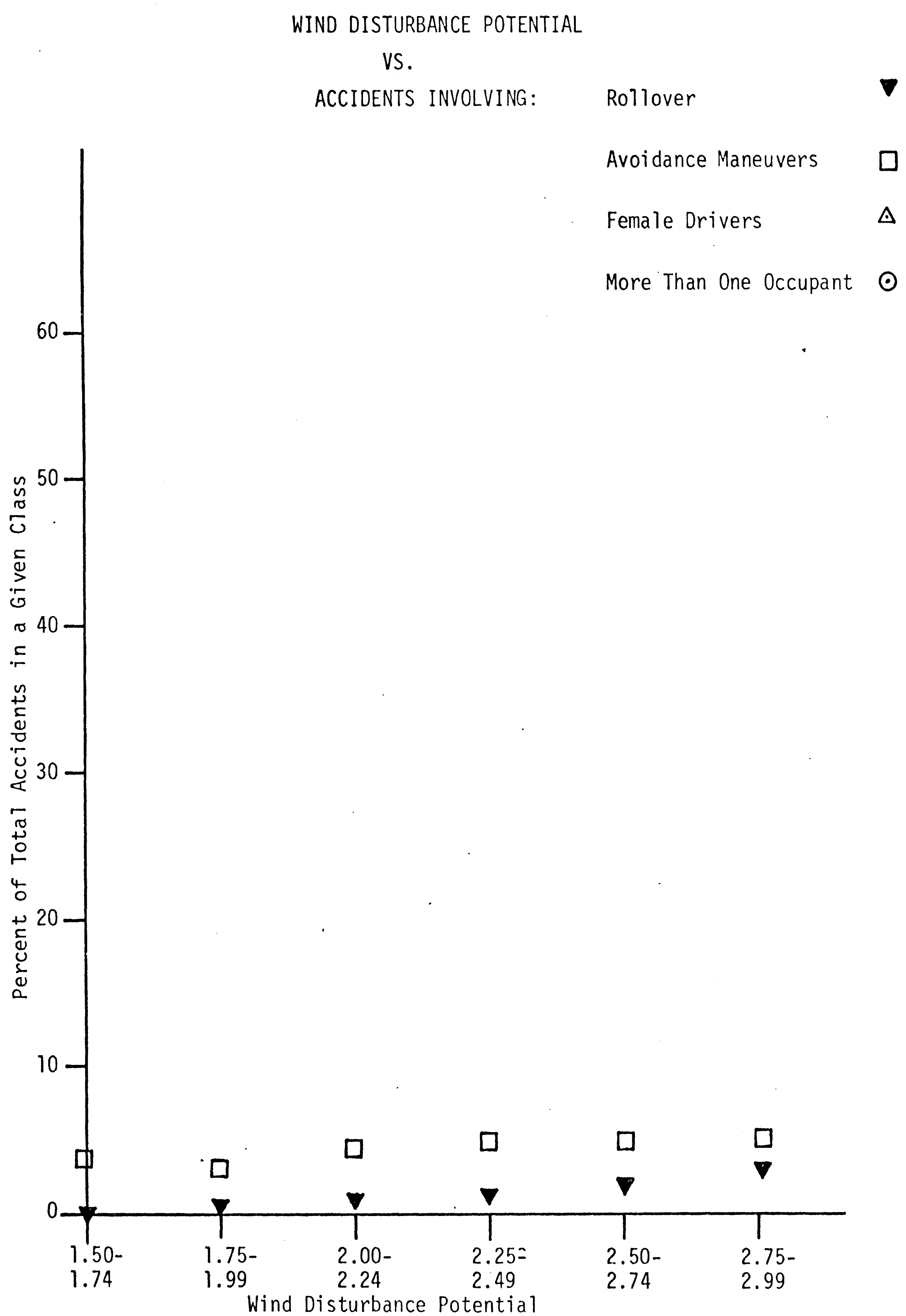
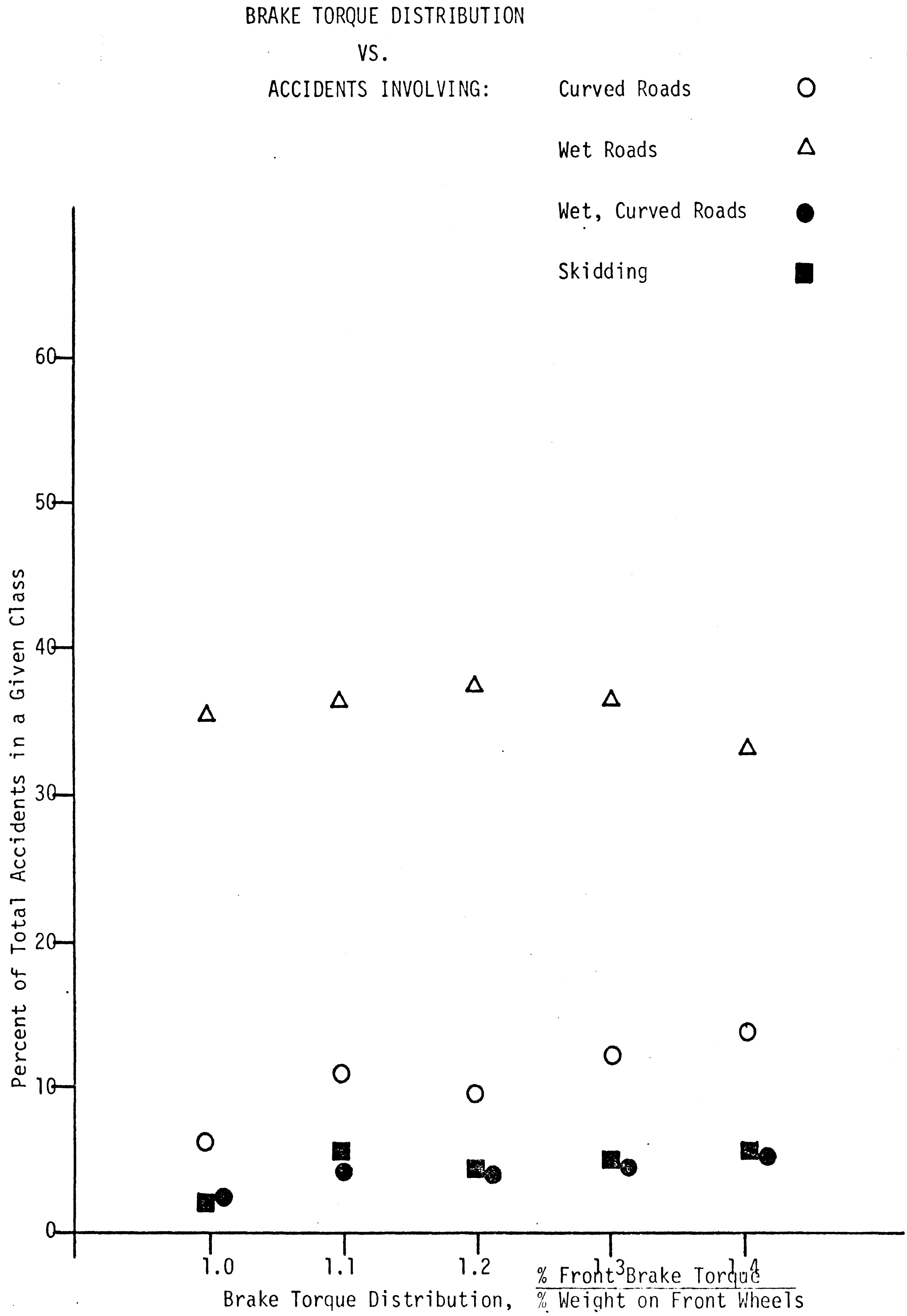

WIND DISTURBANCE POTENTIAL
VS.
ACCIDENTS INVOLVING:
Rollover
Avoidance Maneuvers
Female Drivers
More Than One Occupant
Percent of Total Accidents in a Given Class
60
50
40
30
20
10
0
1.50-
1.74
1.75-
1.99
2.00-
2.24
2.25-
2.49
2.50-
2.74
2.75-
2.99
Wind Disturbance Potential

Figure 7.20



BRAKE TORQUE DISTRIBUTION
VS.
ACCIDENTS INVOLVING:
Curved Roads
Wet Roads
Wet, Curved Roads
Skidding
Percent of Total Accidents in a Given Class
0
10
20
30
40
50
60
1.0
1.1
1.2
1.3
1.4
Brake Torque Distribution, % Front Brake Torque / % Weight on Front Wheels

Figure 7.21

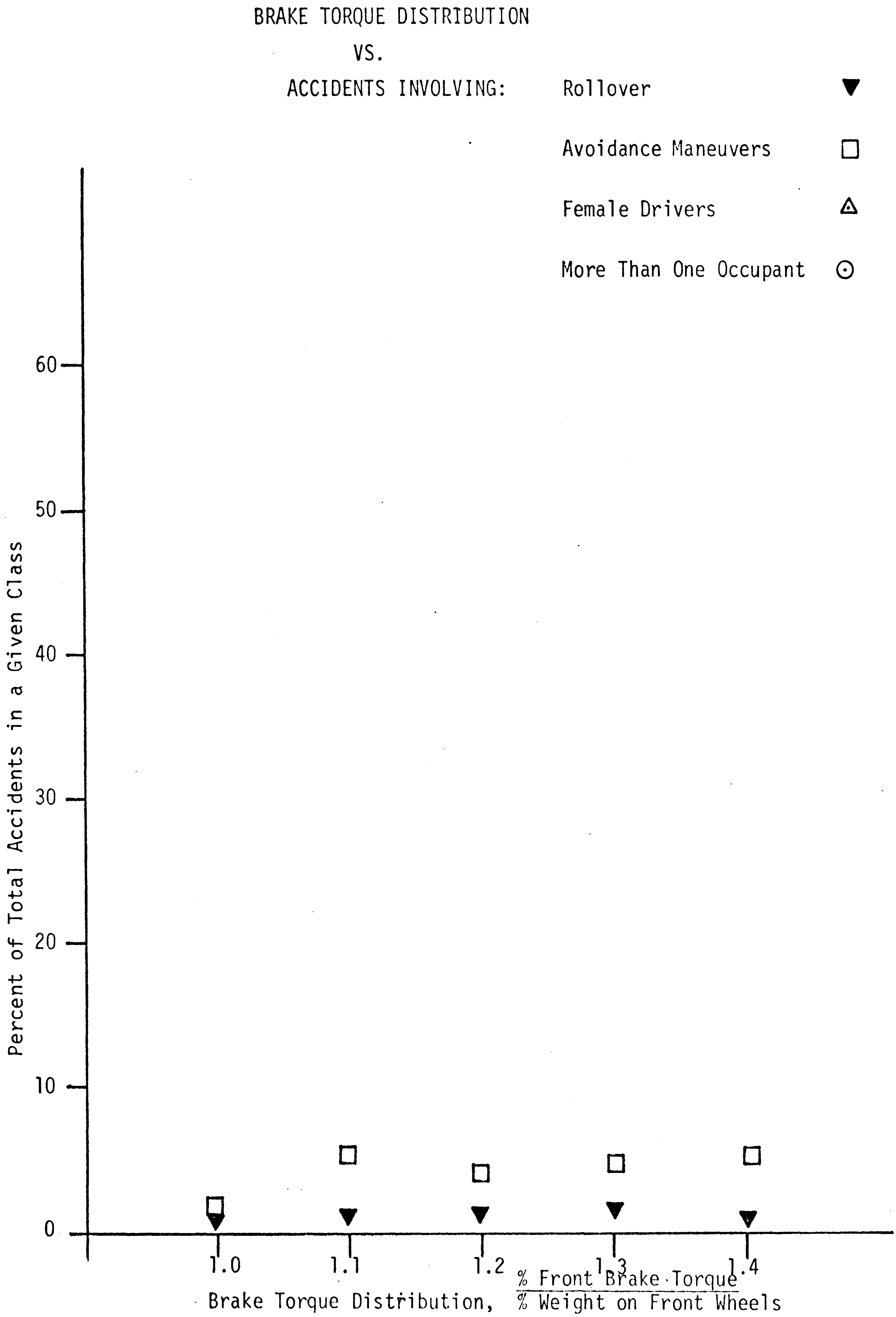

BRAKE TORQUE DISTRIBUTION
VS.
ACCIDENTS INVOLVING:
Rollover
Avoidance Maneuvers
Female Drivers
More Than One Occupant
Percent of Total Accidents in a Given Class
60
50
40
30
20
10
0
1.0
1.1
1.2
1.3
1.4
Brake Torque Distribution, % Front Brake Torque / % Weight on Front Wheels

Figure 7.22

proportion brakes for conditions other than straight-line motion is controversial. Increasing brake proportioning on the front wheels of an automobile tends to decrease the possibility of rear-wheel lockup and should enhance vehicle stability. On the other hand, proportioning more braking capability to the front wheels tends to increase the possibility of front-wheel lockup and thus degrades the ability to steer. The results presented in Figure 7.21 suggest that the latter occurrence is the mechanism that accounts for the observed trends. On the other hand, there is also the possibility that the braking efficiencies (of the vehicles included in this analysis) are significantly less on wet roads in comparison to dry roads, as the brake proportioning parameter is increased. In other words, the data are also possibly explained by a decreased ability to utilize available wet road friction (without wheel lockup) with an increase in the front wheel proportioning parameter. Clearly, more data comparable to that presented in Figure 7.21 should be collected as a means of resolving whether brake proportioning, as commonly carried out to optimize the straight-line braking process, should be influenced by considering the consequences related to the ability of average drivers to brake safely on wet curves.

Although we have plotted only those results which show some consistent trend or relationship, all of the derived data for the additional parameters and indices is given in Appendix E.

7.4 Summary

A methodology to determine the role of vehicle handling in accident causation has been proposed which requires that (1) accident data, (2) handling data, (3) exposure-to-risk data, and (4) image-risk data be collected and analyzed. The method has been (partially) applied, in a very preliminary way, to demonstrate that it is feasible to combine data libraries in fulfillment of the desired objective.

At this point in time, it appears that the methodology, as conceived and proposed, should be applied in a full-scale endeavor addressed to the question of interest. As of this writing, it appears that the developed methodology will require that handling data be collected for approximately 100 vehicle models in order to obtain both a sufficient spread in handling characteristics and an exposure to risk sufficient to produce accident numbers sufficient for analysis. It was also pointed out that the additional data required to implement the methodology should be obtained both within a two-year time frame and within a common geographic area.

The accident data should include at least 300,000 cases, requiring that it be collected through a police accident reporting system by means of a supplemental reporting sheet. The exposure-to-risk data should be acquired both through a mailed questionnaire survey and through interviews at license renewal offices. Vehicle handling performance data should be acquired by means of a dynamic testing activity—both for normal handling and limit handling properties. Finally, image-risk data should be collected by means of automated traffic surveys at selected locations. These surveys should identify driver and vehicle while simultaneously recording such variables as speed, lane of travel, position in lane, car following distance, and weather conditions.

These data would be analyzed to produce true accident rates, namely, rates that are normalized for confounding influences such as driver, exposure, and image factors. On comparing true accident rates with various accident descriptors, we would, hopefully, be able to define the relative accident causation potential that can be associated with a given level of a specific vehicle handling descriptor.

8.0 ACCIDENT RECONSTRUCTION METHODOLOGY

It is generally recognized that indepth accident reconstruction methodology, as currently practiced, is not particularly well suited to identifying the handling characteristics of vehicles as accident causation factors. For a variety of reasons, emphasis is and has been placed on the crash and post-crash phases of the accident—those areas which relate to occupant injury and vehicle crashworthiness. Although it is recognized that these areas are important—and there is no intention to degrade their importance here—emphasis must be placed on different aspects of accident reconstruction if handling-related causation factors are to be exposed. In particular, vehicle handling factors, if such are involved in an accident, influence the pre-crash phase of the accident. To establish beyond question whether vehicle handling factors were involved in an accident, a substantial amount of information appears to be needed. For example, one would like to know the following information:

1. Histories of the driving cues presented to the driver, his or her decision processes, and his or her control actions.

2. The pre-crash path(s) of the vehicle(s) including the length, location, and microscopic characteristics of skid marks.

3. The characteristics of the friction at the tire-road interface.

4. The "handling" characteristics of involved vehicles—as determined by basic design, and as modified by loading, tire pressures, and other first-order effects.

5. The maintenance and repair status of the involved vehicle—particularly in relation to identifying the influence of mechanical condition as a factor other than the influence of basic design.

6. The physical condition and capacities of the driver(s) (e.g., alertness, experience, reaction capacity, physical strength, etc.).

7. The ergonomic matching of the driver with the vehicle, i.e., the arrangement and placement of driving controls and the required forces for their manipulation.

8. The ambient environment.

9. The macroscopic characteristics of the roadway, e.g., geometric alignment, pavement roughness, sight obstructions, etc.

(It should be emphasized that the interest here is not with vehicle defects as accident causative mechanisms. Rather, the concern is with the performance characteristics of new and in-use vehicles, that is, are there vehicle performance factors that lead to an over- or underinvolvement in accidents?)

Obviously, some of these elements are, and will be, difficult to obtain—the first item listed above representing a good case in point. Without a recording device on the vehicle it will, at best, be difficult (if not impossible) to establish the sequence of cue assimilation, driver decisions and driver control actions in the pre-crash accident phase. Yet the historical record of this phase is a virtual necessity in establishing the breakdowns in the vehicle/driver/road-surface system that led to the ultimate crash.

Regardless of the difficulties involved, however, it appears that there are areas in which accident reconstruction methodology can be upgraded in order to better understand the pre-crash phase. Such upgrading is highly relevant to the objectives of this study and, consequently, a portion of the study effort was devoted towards upgrading specific aspects of the pre-crash reconstruction process and the associated reporting procedures. These topics are treated below.

8.1 Accident Reconstruction Aids

In this study, five topics of relevance to the reconstruction and analysis of the pre-crash interval were examined, namely:

- analysis of skid marks
- determination of pavement skid resistance
- measurements of pavement slope (superelevation and grade), curve speed, and light intensity
- measurements of driver reaction time, pedal force strength, and grip strength
- determination of the maintenance/repair status of the vehicle of interest.

The first two topics are treated below, in some depth. The remaining topics are treated by reviewing the equipment that was developed specifically to serve as a set of accident reconstruction tools. At the end of this section, reference is made to the need for an accident reporting form that is particularly suited for investigating the role of vehicle handling in accident causation. Since the comprehensive supplemental form entitled "Vehicle Handling Supplement" (developed herein as an addendum to the CPIR form now being used in MDAI activities) is a very large document, it is not included in the body of this report. The reader will find this supplemental form in Appendix D preceded by a short exposition of the philosophy governing its development.

8.1.1 Skid Mark Analysis. Skid marks, if present, can be a valuable source of information at an accident scene. One of the objectives of this study was to determine the extent to which skid marks can be analyzed and interpreted to yield considerably more information than is commonly extracted at present.

The approach to skid mark analysis begins with the recognition that, in theory, information should be contained in three aspects of skid marks, viz., (1) the gross length and curvature of the marks, (2) the short irregularities in the gross features, and (3) the macroscopic tread element patterns. Skid mark lengths are used in accident reconstruction to determine braking distance (and hence stopping distance or distance over which a speed change has occurred), with curvature used to indicate the presence of a critical speed (i.e., that speed at which a vehicle just begins to lose traction when following a curved path). Short irregularities in skid marks such as collision scrubs or braking gaps, etc., can be used to pinpoint events in a collision or to pinpoint driver actions. Both of these topics have been treated extensively in the literature [47] and will not be discussed further here.

Tread element patterns (or lack thereof) in skid marks can be used to determine the occurrence of braking, steering, accelerating, or combinations thereof, on the part of a driver. Such patterns can consist of actual tread imprints, rib marks, tread edge marks, and striation marks. While the presence of tread element patterns in skid marks has been mentioned in the literature, the full meaning of such patterns was not known. Accordingly, work was undertaken in this study to determine the information that can be extracted from tread element patterns. This investigation led to the following conclusions:

1. Actual <u>tread imprints</u> (i.e., a deposited image of the tire tread) only occur in straight-line braking and then only under longitudinal slip conditions of between 5 and 20%. (One hundred percent longitudinal slip represents locked-wheel braking, while braking at less than 100% indicates the braked wheel is still partially rolling.)

2. <u>Tread imprints</u> very probably only occur in skid marks produced by front tires and even then are undoubtedly quite rare since:

    a. passenger car tire tread imprints are not easily discernible unless a tire loading condition exists which is equivalent to at least a 40% weight transfer to the front tires;

b. incipient wheel lockup is virtually destined to occur for any slip condition greater than 20% because of the brake force-slip ratio characteristic of the pneumatic tire.

3. Tread rib marks only occur in straight-line braking and then only when the wheel is locked.

4. Tread edge marks are made by front tires which are highly loaded as the result of the load transfer produced by braking.

5. Striation marks are present in skid marks when a tire is being subjected to a lateral slip condition, i.e., when a vehicle is turning or cornering.

6. Striation marks make an angle to the gross direction of the skid mark which is dependent both on the lateral slip angle and the longitudinal slip condition. The angle is independent of vehicle speed.

7. Striation marks appear as intermittent skid mark elements, two to three inches in width, which are spaced at intervals of two to four inches on the pavement.

8. The width and spacing of striation marks is undoubtedly influenced by the interior tread pattern of the tire and by the edge pattern along the side of the tread. Even so, tires such as the ASTM tire with a simple circumferentially-ribbed tread and a featureless edge pattern exhibit the same intermittent striation marks as do fully-treaded tires. A typical set of striation marks made with an ASTM tire under laboratory conditions is shown on Figure 8.1.

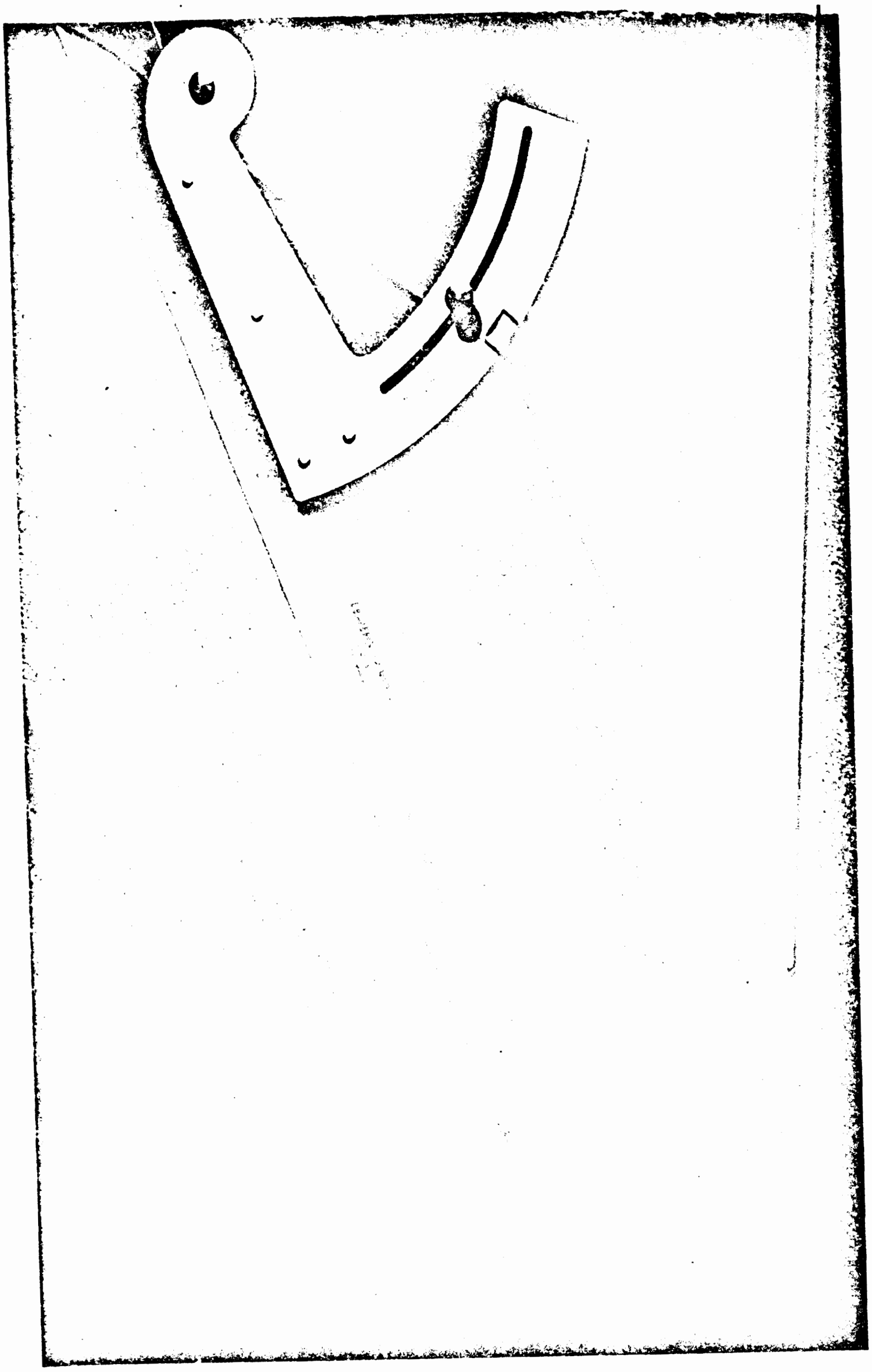


Figure 8.1

9. The appearance of skid marks is not grossly affected by tire pressure except when the tire experiences a vertical deflection greatly in excess of its deflection at rated load and pressure.

10. Tire load and traveling speed influence the darkness of skid marks. Heavier loads and lower speeds produce darker marks.

As mentioned, the angle that a striation mark makes with the gross direction of a skid mark is dependent upon the prevailing conditions of longitudinal and lateral slip. This observed dependence is consistent with the recognition that the motion of the tire tread across the pavement surface is the result of (1) the translational velocity of the wheel and (2) the rotational velocity of the tread about the spin axis of the wheel. A kinematic description of the motion is depicted in Figure 8.2 where:

$\overline{V}$ = translational velocity of the wheel hub

$\overline{x}$ = a horizontal axis located in the centerplane of the wheel passing through the wheel hub (or axle)

α = lateral slip angle or steer angle of the tire with respect to the direction of translational motion

R_e = effective rolling radius of the tire

Ω = angular velocity of the tire

$\overline{V}_t$ = velocity of tread element along the road surface

θ = angle of a striation mark (or tread element velocity vector) with respect to a line which is perpendicular to a tangent to the skid mark.

From Figure 8.2 it is evident that

$$V_t \cos \theta = R_e \Omega \sin \alpha \tag{8.1}$$

and that

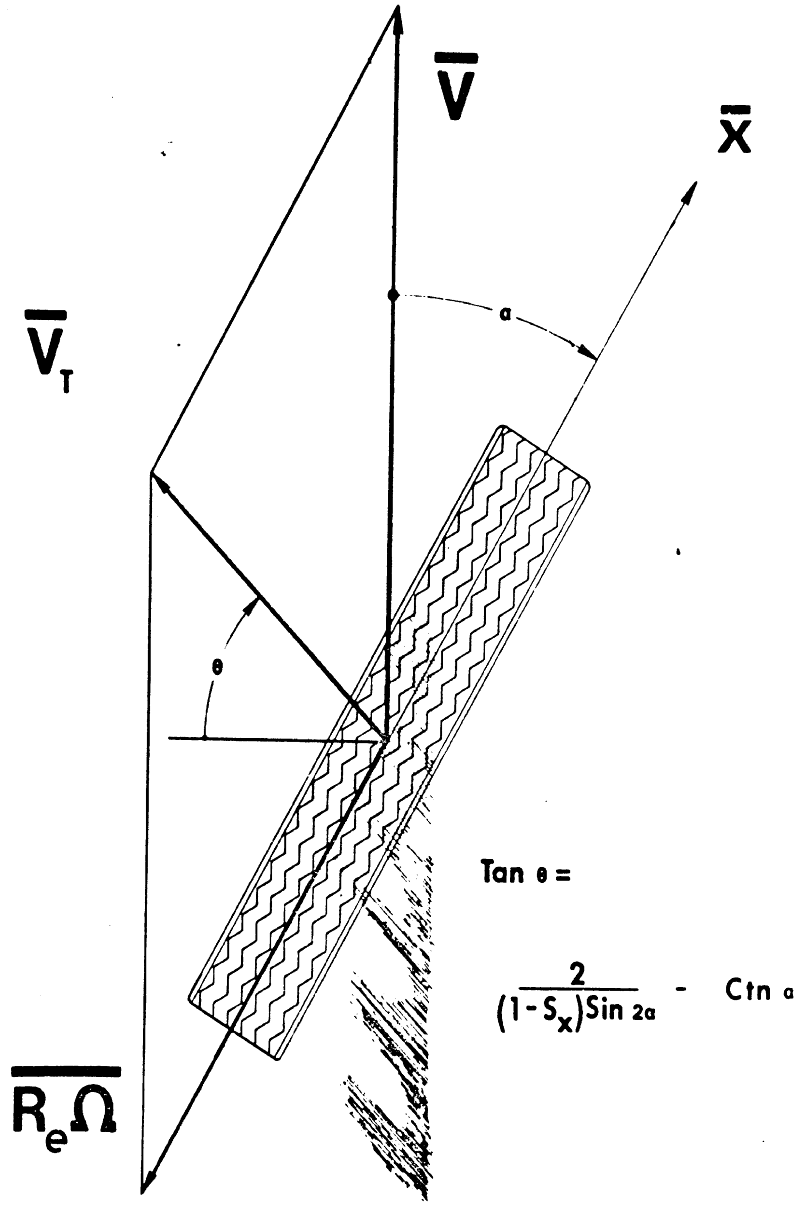

$\bar{V}$
$\bar{X}$
$\bar{V}_T$
a
θ
$\overline{R_e\Omega}$
Tan θ =
$\frac{2}{(1-S_x)\sin 2\alpha}$ - Ctn α

Figure 8.2

$$V_t \sin\theta = V - R_e \Omega \cos\alpha \tag{8.2}$$

On dividing (8.2) by (8.1), the following expression for the angle, θ, is obtained:

$$\tan\theta = \frac{V}{R_e \Omega \sin\alpha} - \operatorname{ctn}\alpha \tag{8.3}$$

Examination of the kinematics of tire motion with braking applied (see Figure 8.3) shows that

$$R_e \Omega = V(1-s_x)\cos\alpha \tag{8.4}$$

where

$$s_x = \frac{V_{cx}}{V_x} \tag{8.5}$$

$$= \text{longitudinal slip parameter}$$

$$V_{cx} = \text{longitudinal slip velocity}$$

$$V_x = V\cos\alpha \tag{8.6}$$

Substituting Equation (8.4) into (8.3) and rearranging yields:

$$\tan\theta = \frac{2}{(1-s_x)\sin 2\alpha} - \operatorname{ctn}\alpha \tag{8.7}$$

This latter equation is the desired expression for the striation angle as a function of longitudinal and lateral slip. It may be noted that if $s_x = 0$, then $\alpha = \theta$ and the striation angle is

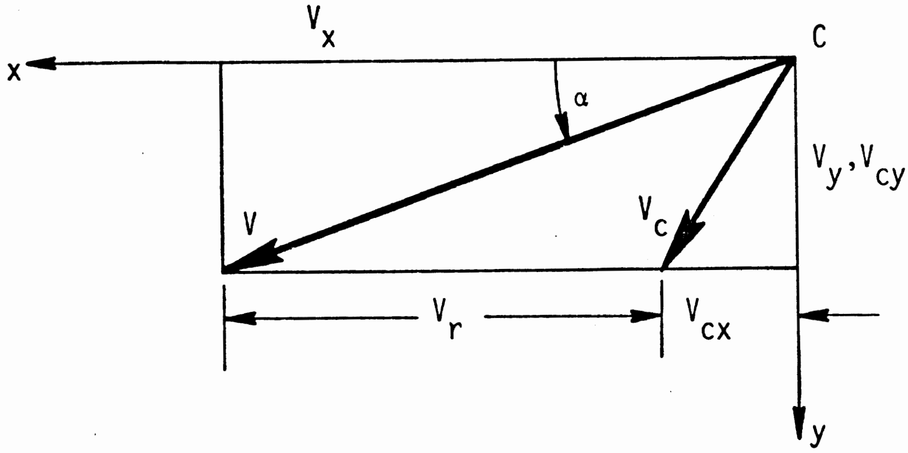


Figure 8.3. Tire kinematic conventions

equal to the slip angle. Similarly, if $s_x = 1$, $\theta = 90°$ and the striation marks become colinear with the direction of the skid mark. The independence of the striation angle with velocity is clearly evident.

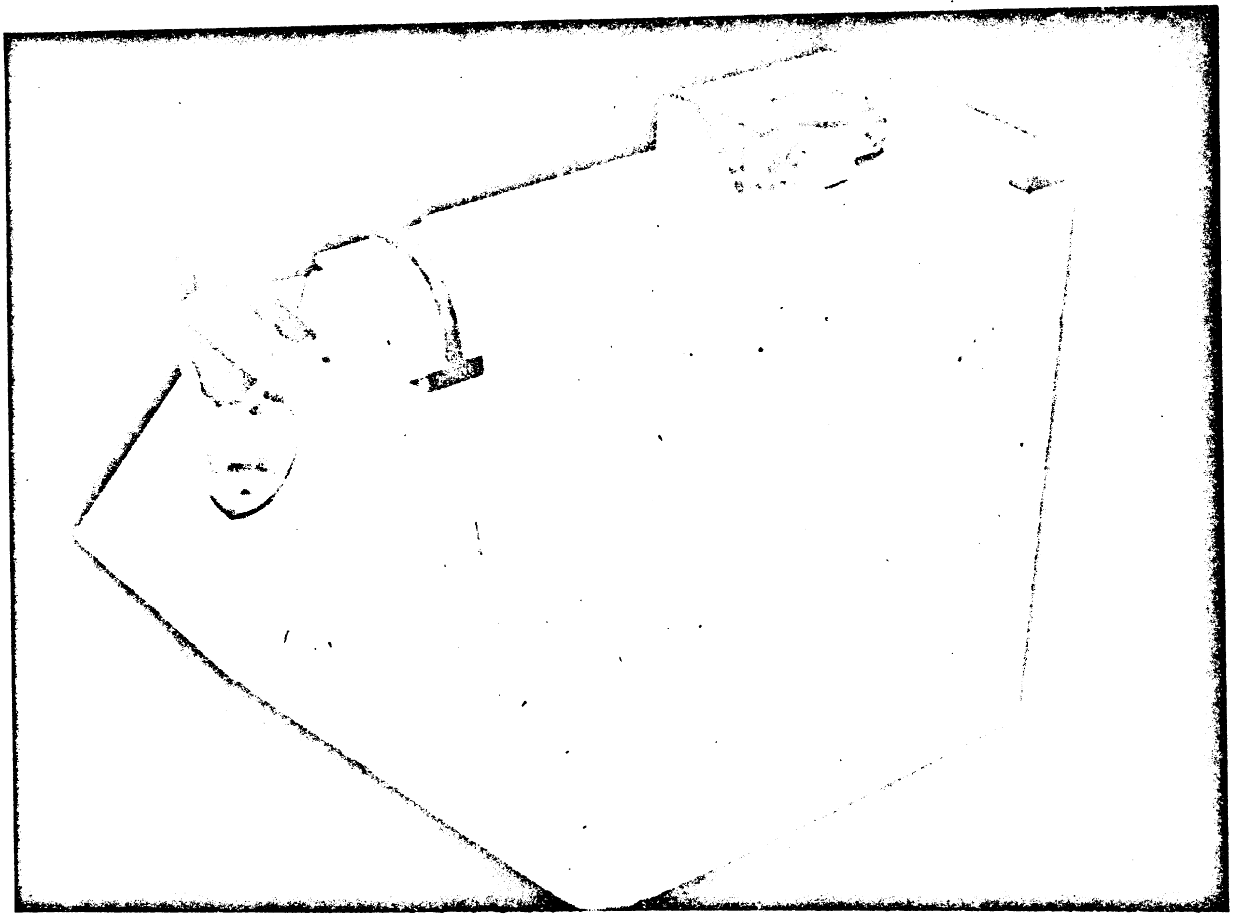
At the scene of an accident, the only information available to an investigator would be the angle of the striation marks. From Equation (8.7) it is clear that knowledge of the striation mark angle is not sufficient to uniquely determine values for longitudinal and lateral slip. There are, however, some deductions that can be made at the accident scene, viz.:

1. If the angle of the striation marks is between 0° and 90°, some steering action is taking place.
2. If the striation marks are parallel to the axis of the skid mark, then <u>only</u> braking action is taking place.
3. If the striation angle is greater than 30° but less than 90°, then a combination of steering and braking is occurring. (The maximum front tire steer angle for a typical passenger car is no more than 30°. Any striation mark angle greater than 30°, then, must result from a combination of steering and braking. Note that $\theta = \alpha$ when $s_x = 0$.)
4. If the striation angle is less than 90°, then the longitudinal slip ratio, s_x, is not likely to be greater than 20%. (As noted earlier, incipient wheel lockup generally occurs for slip ratios greater than 10 to 20% which leads immediately to values of θ of 90°.)

8.1.2 <u>Pavement Skid Resistance</u>. The frictional quality of the road surface is an important piece of information when an accident is being reconstructed. This statement is particularly true if skid marks are present, since the vehicle velocities derived from the length or curvature of skid marks is directly dependent upon the coefficient(s) of friction assumed to exist between tires and the road surface. Typically, an accident investigator estimates the applicable coefficient of friction by resorting to one of the many tables of such coefficients that have been published over the years, e.g., Reference 47. There is little question, however, that such practices can and do lead to large errors.

Ideally, the best way to determine the maximum forces that could be generated by the tires of a vehicle on a given surface would be to test one or more of its tires with a suitable test device on the surface upon which the accident occurred, preferably right after the accident. Several tests at speeds bracketing the accident velocities would be necessary. Clearly, such a procedure is impractical. Nevertheless, investigators still need a uniform (and reasonably accurate) procedure for assessing the frictional quality of a given section of road, a procedure that can be rapidly carried out at the accident scene. An optimum procedure would account for the tires involved and the pavement surface in combination. A more practical approach, however, would involve separate measurements of (1) the tires and (2) the road surface. This latter course is viewed as being the only viable course and is the one adopted here. Basically, methods were developed for incorporation into an accident investigation procedure which involve characterizing (1) pavement surfaces by photo-interpretation analysis and (2) tires by wear and descriptive labels.

Over the past several years, Schonfeld, at the Ontario Department of Highways, has developed a method for determining pavement skid numbers by means of a stereo-photograph analysis technique [48, 49]. In applying this method, it is recommended that five to ten pairs of stereo photographs be taken of the pavement section of interest. The acquisition of these stereo pairs is facilitated by use of a specially constructed camera box equipped with a 35 mm camera and flash-light. (Figure 8.4 shows a box constructed for this purpose.) The stereo pairs can then be viewed through a stereo projector so that an observer is afforded a



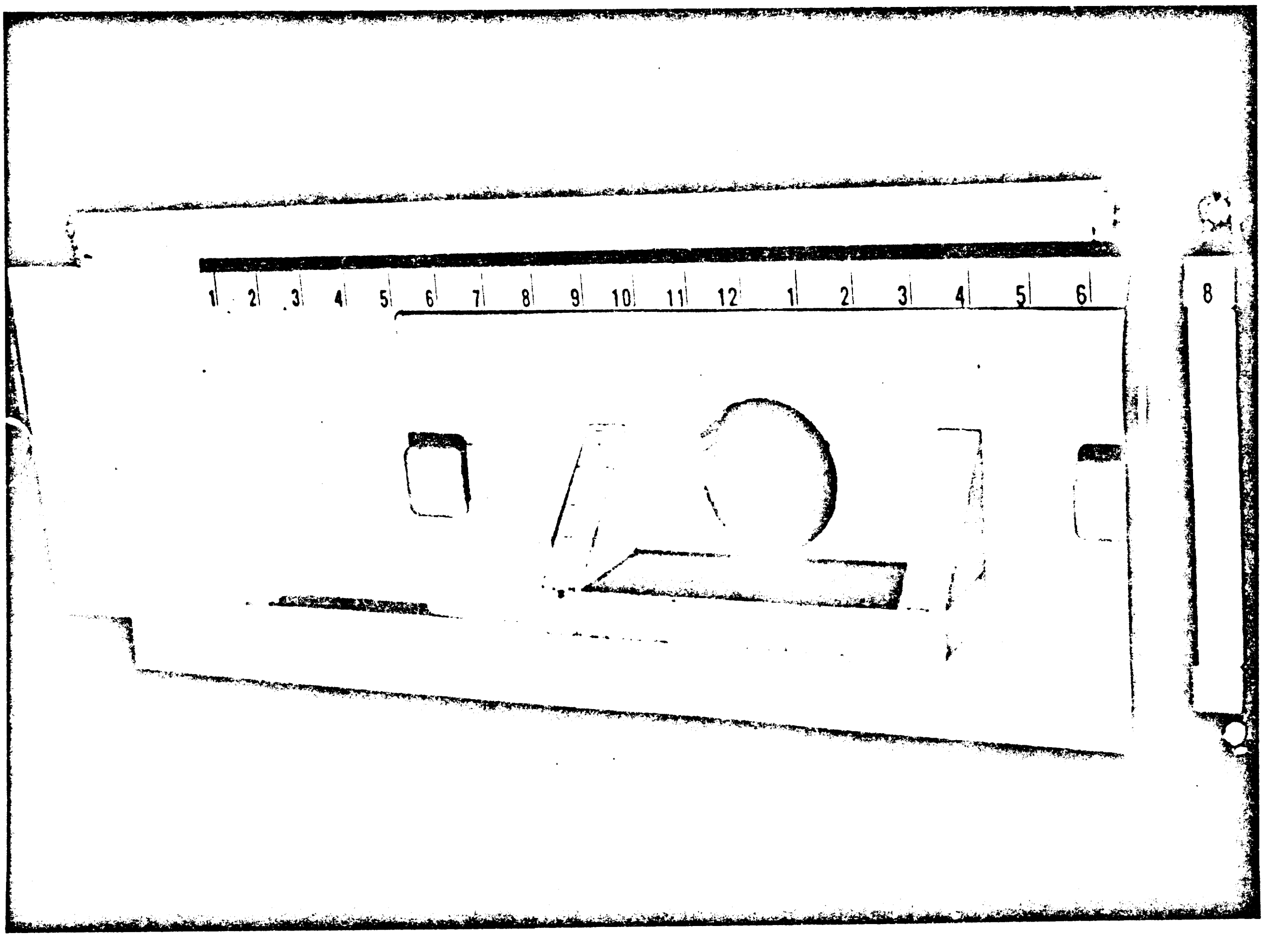


Figure 8.4

three-dimensional perspective of the pavement surface of interest. Figure 8.5 shows such a projector with two sets of stereo pairs and a reference wedge for estimating surface projection dimensions. A typical set of stereo pairs for a fine aggregate asphalt surface with a light coating of Jennite is shown on Figure 8.6. Note the reference wedge and scale which are slightly displaced in one picture with respect to the other.

The skid number of the sample is determined by classifying the texture elements in the sample in accordance with the seven groups of texture parameters which earlier investigators found to have a recognizable effect on pavement skid resistance. These parameters are:

1. Height - The most prevalent height of surface projections in the sample, i.e., projections which may come in contact with the tire.
2. Width - The most prevalent width of surface projections in the sample.
3. Angularity - The prevalent shape of surface projections.
4. Density - The density of spacing of surface projections.
5. Projection Texture - The size, sharpness, or roundness of the micro-projections on the surface of the stone aggregate projections.
6. Background Texture - The size, sharpness, or roundness of the micro-projections on the surface of the filler material between the stone aggregate.
7. Undrained Cavities - The proportion of cavities (depressions or holes) in the background surface which do not have exit drainage channels and which hold water under wet surface conditions.

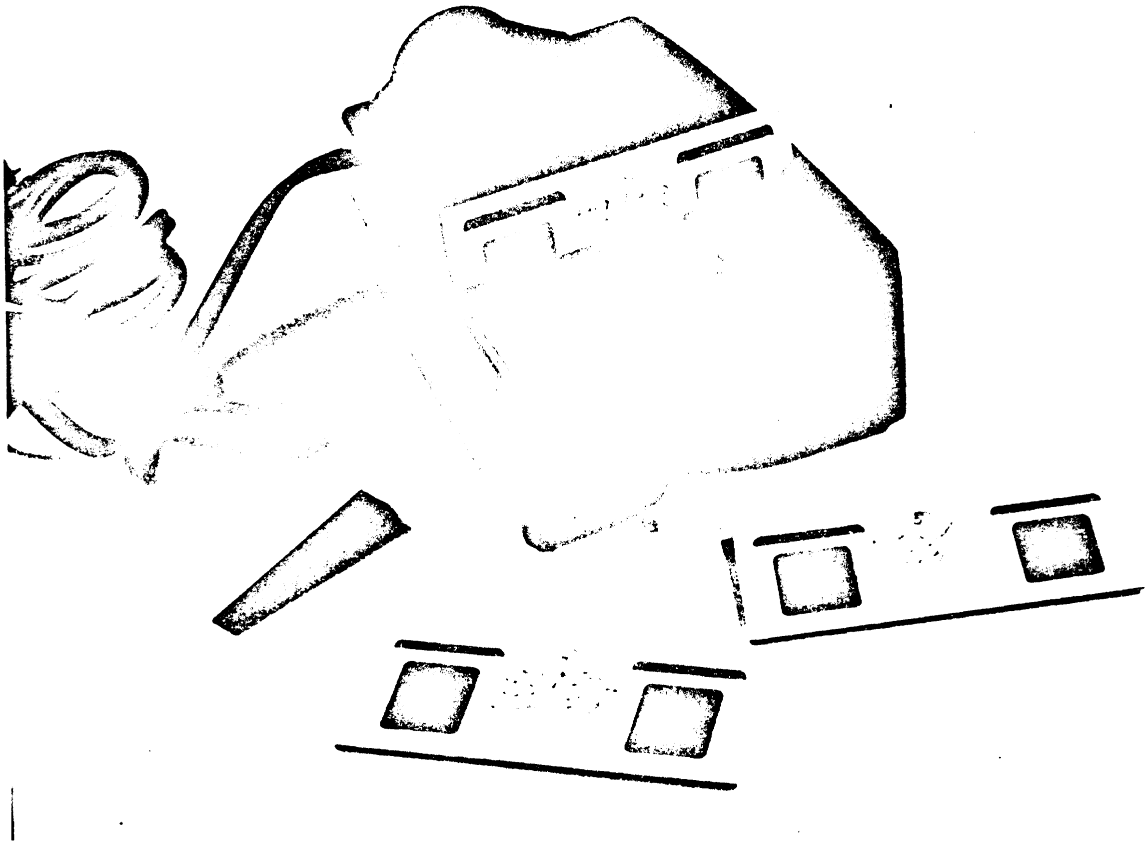


Figure 8.5

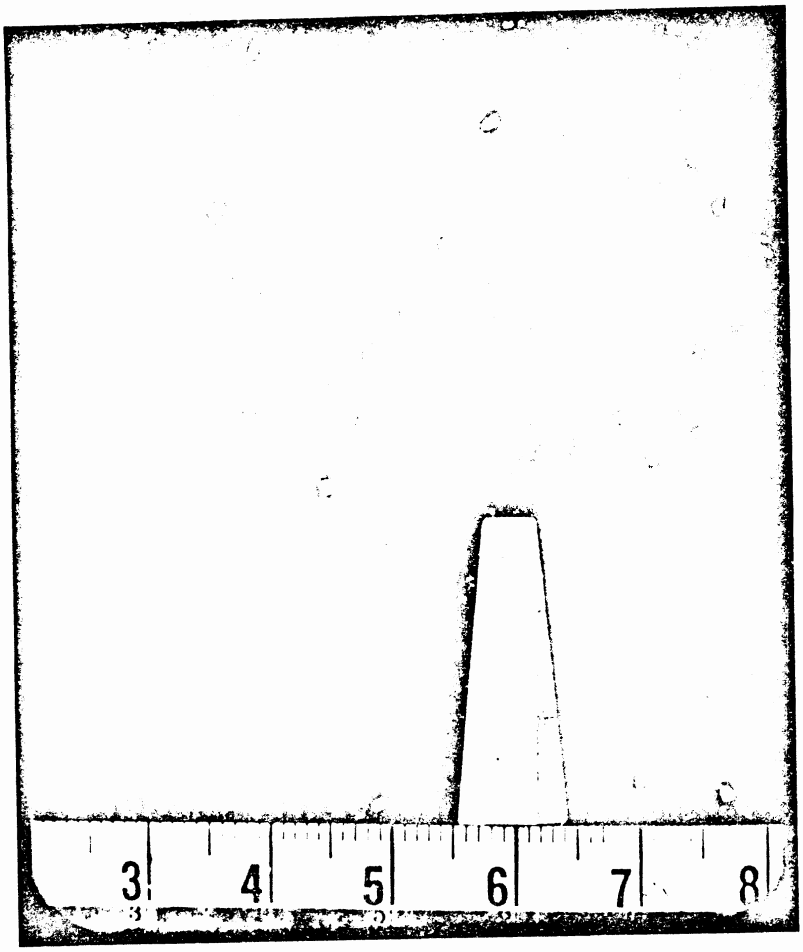


Figure 8.6

By weighting each texture parameter according to a predetermined scheme, a skid number is obtained which has been demonstrated to compare well with that yielded by the ASTM skid test procedure. The actual mechanism of determining the skid number for a surface is carefully laid out in two references [48, 49] which should be consulted by those interested in implementing the process. Alternatively, arrangements can be made to have the Ontario Department of Highways determine skid numbers on a contractual basis from stereo pairs supplied to them from other organizations.

As a second alternative, the Schonfeld method has recently been automated by adapting the stereo-photgrammetric techniques of aerial mapping to obtain a three-dimensional contour of a section of pavement surface [50]. The contour map is reproduced electronically, resulting in a digitized set of data that describes the three-dimensional surface. Computer algorithms are used to (1) process these data and (2) classify the surface texture automatically, for example the average height, width, and angularity for each of the macro- and microparticles on the surface are calculated a la the Schonfeld method and an estimate of the pavement skid number is produced. Clearly, the main advantage of the automated method is the removal of the human analyzer from the skid number determination process, resulting in a more rapid and accurate processing of the field data (i.e., the stereo pairs).

The advantages of using the Schonfeld method in accident reconstruction lie with the quickness that the necessary photographic information can be acquired. Typically, the camera box can be placed over a selected pavement surface and photographs taken in a matter of two or three minutes. No elaborate skid trailers, recording devices and similar equipment is necessary. The box and photographic equipment are easily transported by car. Further, one set of stereo photos provides all the information necessary to derive the variation in skid number with respect to speed.

(A pavement skid number, it may be recalled, is a number which, when divided by 100, constitutes the coefficient of friction that exists between a road surface and a non-rotating standard test tire [51, 52]. The test is ordinarily conducted at 40 mph with water being deposited in front of the test tire in order to yield a "uniform" water coating of 0.02 inch over the test surface. The resulting skid number is a standard measure of the surface skid resistance at 40 mph. To obtain the skid resistance variation with speed, tests at other speeds are necessary. Since the skid number represents only the pavement skid resistance seen by a single tire, its relationship to the coefficient of friction between the road surface and the tires on an actual vehicle is rather indirect. Further, the test is intended to establish wet surface skid resistance only. Estimates of coefficient of friction for dry surfaces must be made by other means. Fortunately, however, dry skid resistance is much less variable than that under wet conditions with values of 0.8 to 1.0 being typical coefficient of friction levels covering a wide range of tire and surface conditions [53].)

As has been mentioned, the determination of the coefficient of friction prevailing during an accident requires both a knowledge of the surface and the tires mounted on the vehicle. Although the characteristics of the surface can be determined using the Schonfeld method, those of the tire must be established by other means and entered into the accident record in a manner such that the subsequent reconstruction process is facilitated. The Vehicle Handling Supplement to the CPIR accident report form (as presented in Appendix D) suggests a suitable data collection format.

8.1.3 Reconstruction Tools and Equipment. Several additional tools and equipment developed or acquired during the project for aiding in the reconstruction of the pre-crash accident phase are deserving of comment in this section of the report.

Figure 8.7 shows a set of sample impressions taken from a pavement surface with the illustrated clay-like modeling compound. Such impressions are valuable in that they provide an actual three-dimensional record of the pavement surface which can be easily stored for future reference. Further, the impressions

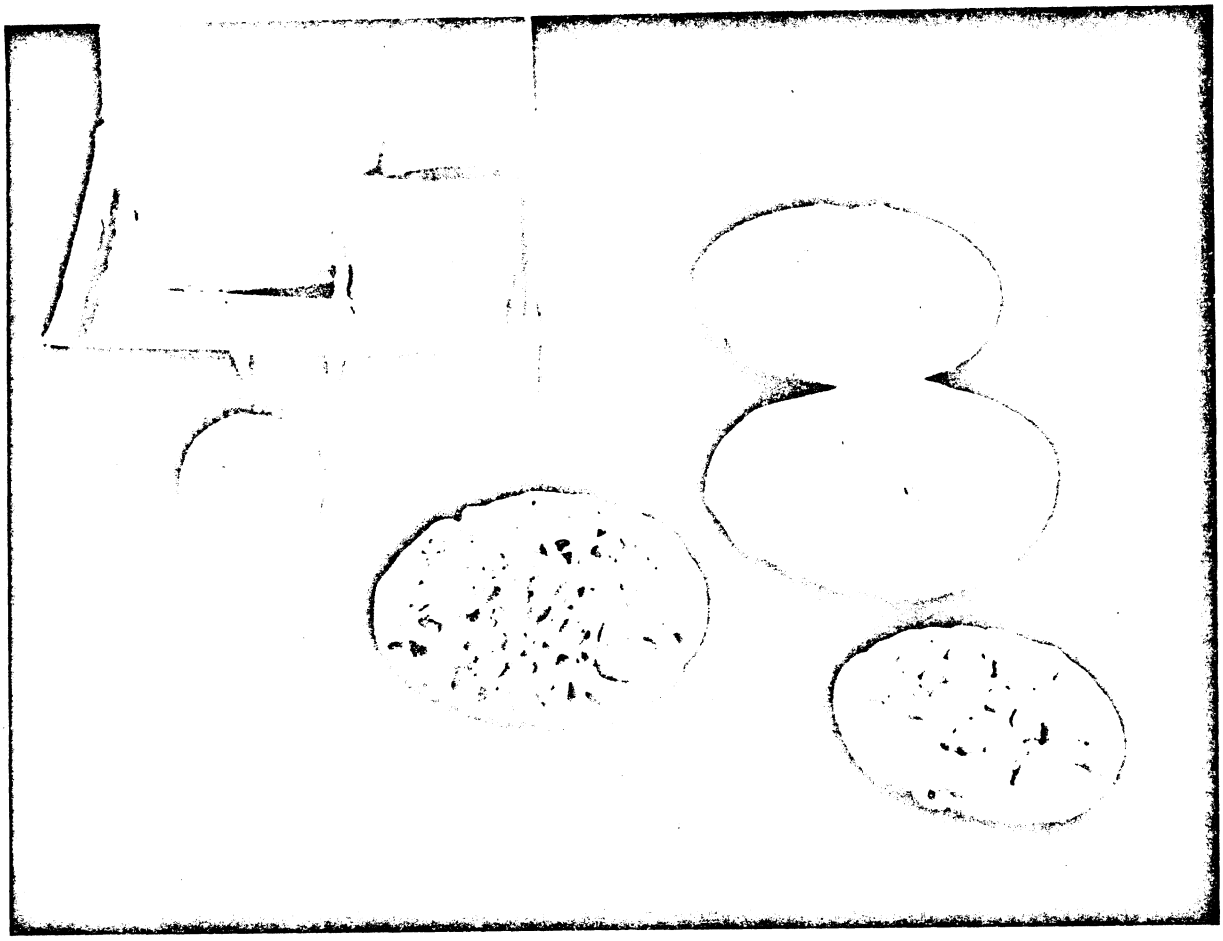


Figure 8.7

constitute a supplementary piece of information which can be used in conjunction with the stereo photographic process.

Figures 8.8 and 8.9 show two views of an adjustable level which can be used for making rapid measurements of pavement slope (crown, grade, or superelevation). The modified level is simply laid on the pavement surface, and the movable level is adjusted and fixed at the level position. Readings on the scale are in units of slope (in/in, ft/ft, %) as per the highway design convention. The adjustable level was designed to replace the conventional and cumbersome surveying technique using a transit and stake.

Figures 8.10 and 8.11 show a precision tire pressure gauge and a contour gauge, respectively. This pressure gauge greatly facilitates acquisition of accurate tire pressure measurements on vehicles involved in accidents. Tire gauges commonly used in service stations and sold for measuring inflation pressure are notoriously imprecise and variable with temperature. Since tire pressure has a first-order effect on vehicle handling performance, accurate tire pressure measurements are a necessity in any accident reconstruction effort concerned with such performance.

Likewise, tread wear is known to have an important effect on handling performance, particularly under limit maneuvering conditions. Typically, a measurement of tread depth has been used to characterize tire wear. The difficulty with this single measurement is that there is no uniform standard for making this depth measurement and, further, a single tread depth measurement in no way characterizes the total wear state of a typical tire. Tire wear can be uneven and asymmetric as the result of misalignment, wheel imbalance, loose wheel bearings, high cornering forces, etc. The contour gauge illustrated in Figure 8.11 provides a means for obtaining a complete profile of the cross-section of the tire tread, yielding an excellent picture of the state of tread wear.

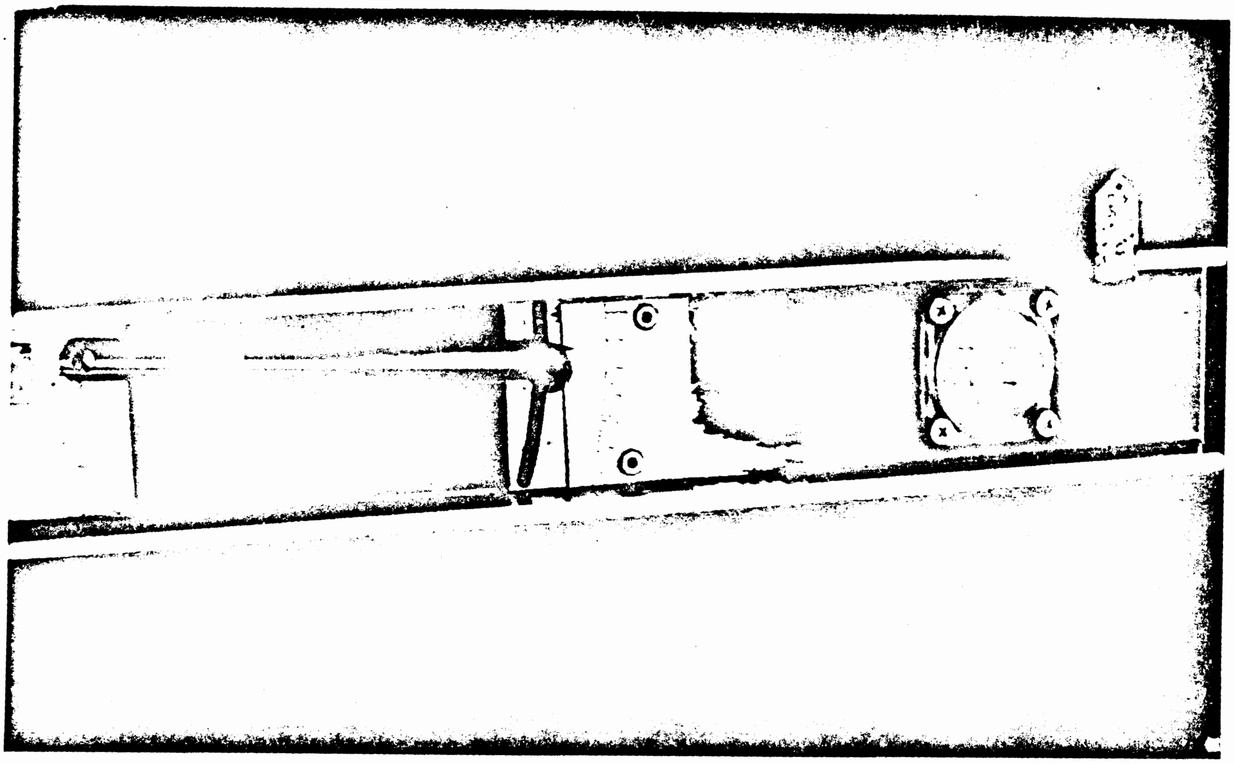


Figure 8.8

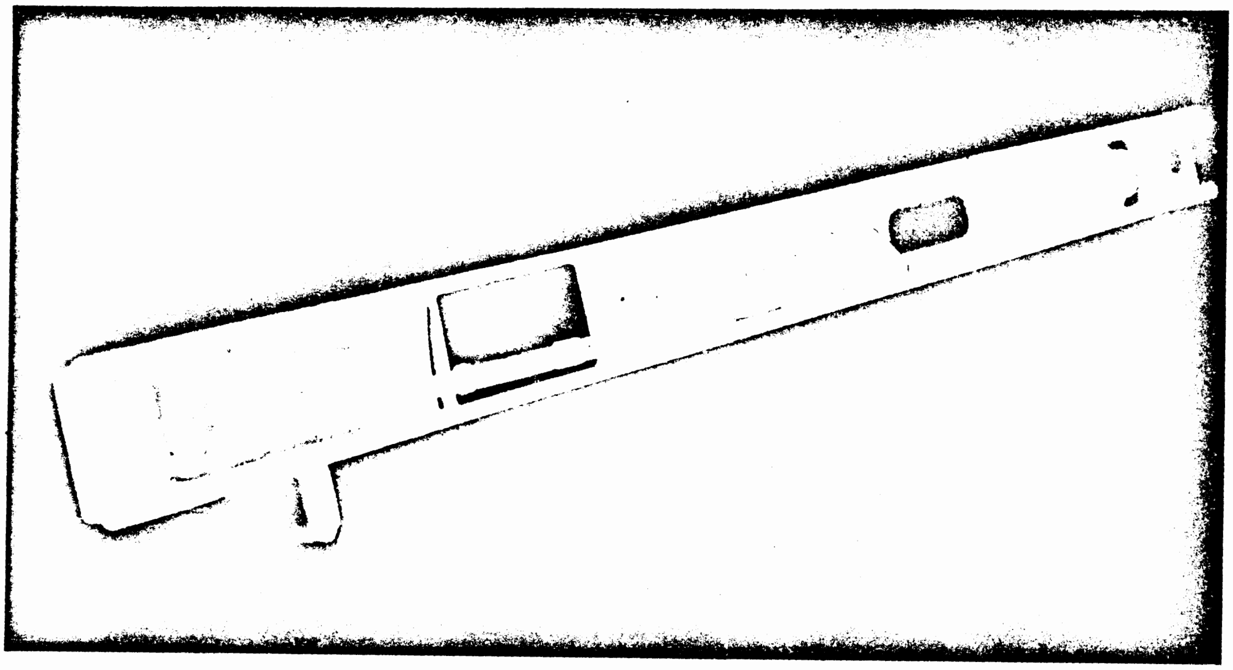


Figure 8.9

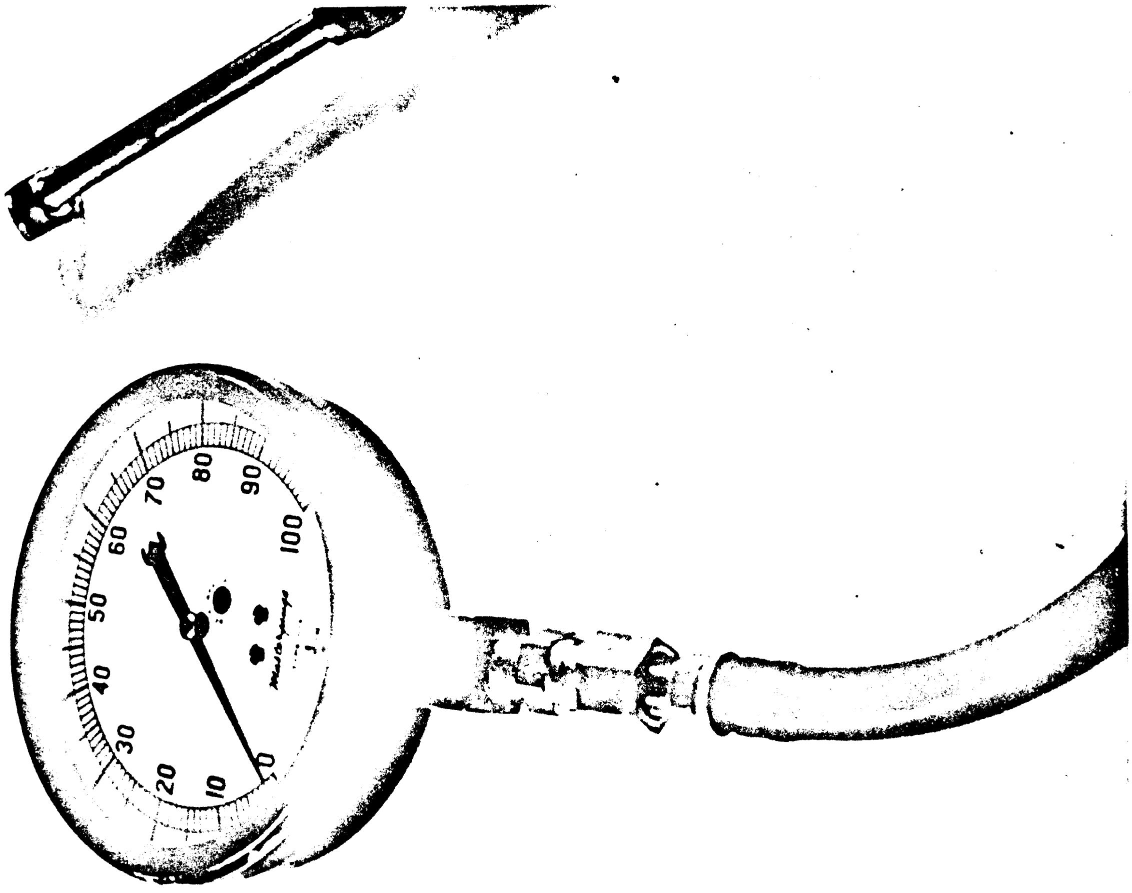


Figure 8.10

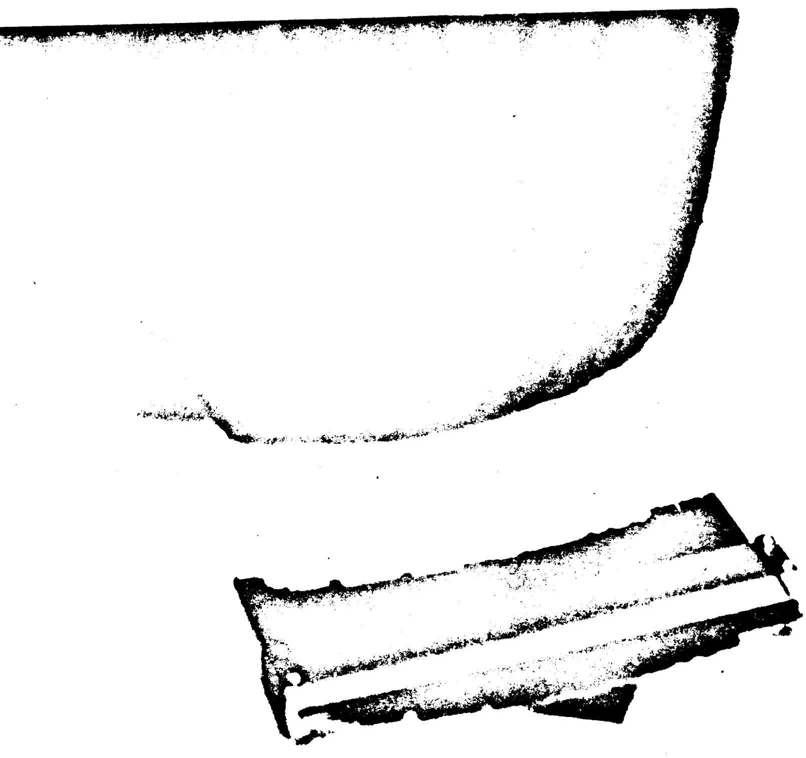


Figure 8.11

Figures 8.12 to 8.14 are illustrations of devices which have been fabricated or adapted for use in determining driver capabilities. Figure 8.12 is an illustration of a device which can be used to measure driver reaction time. The device can be used to test simple reaction time or reaction time including a binary decision process. The device is set-up such that an operator administering the test presses a button on one panel which simultaneously causes a clock to start and one of two lights to go on on a second panel. The person taking the test then presses an appropriate button on the second panel to extinguish the light. Simple reaction time is measured when the subject knows which one of the two lights will be illuminated on the second panel. Reaction time including a binary decision is measured when the subject does not know which of the two lights will go on.

The device shown in Figure 8.13 was developed for measuring a driver's strength in pushing a foot pedal. The device can be adjusted to the physical dimensions of the subject so that maximum force can be applied. The purpose of the device is to determine the strength of the driver in applying brake force. Studies have shown [54] that at least 5% of the female driver population is not capable of exerting enough brake pedal force to produce maximum deceleration in the average passenger car. The influence of this finding on accident causation is not known and therefore should be investigated.

Figure 8.14 shows a device suitable for measuring the strength of a driver's grip. As with the pedal-force device, the purpose of measuring grip strength is to obtain an understanding of the relationship between this index of driver capability and accident causation. The grip strength test is easy to administer and the device is clearly very portable. If grip strength should prove to correlate well with pedal-force strength, the latter test, being more difficult to apply, could be dispensed with.

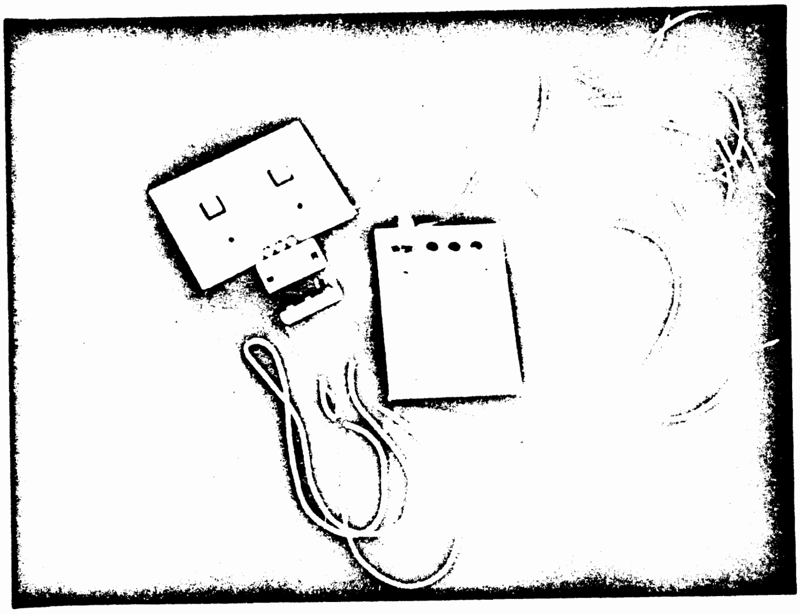


Figure 8.12

Figure 8.13

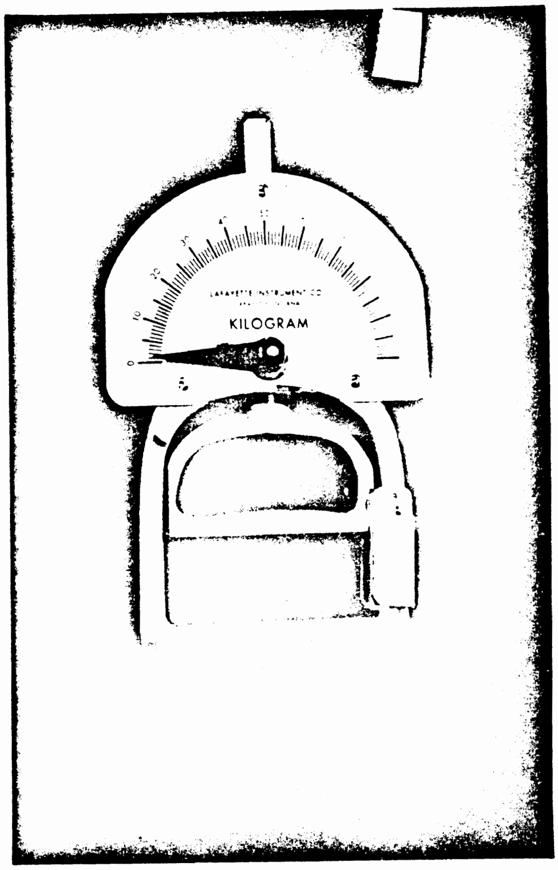


Figure 8.14

The reconstruction tools and equipment illustrated in Figures 8.7 to 8.14 are intended for use with the accident reporting form developed in the course of this study.

8.2 Reporting Procedures

A Vehicle Handling Supplement to the CPIR form was developed for purposes of gathering information which could be used to identify vehicle handling factors in an accident. The form is presented in Appendix D. In keeping with the definition of vehicle handling adopted in this report, the supplement requires that data be obtained to define the driver/vehicle/road-surface system. As has been discussed earlier, the task of separating out vehicle design and performance factors as accident causes requires that other factors, i.e., those related to the driver and the road, must be carefully identified. Thus, the supplement is divided into sections which deal with the following five categories of information:

1) Environment
2) Roadway
3) Vehicle
4) Operator
5) Accident Kinematics

The supplement is assembled in a modular fashion such that parts (or pages) can be added or deleted depending upon the case under study. For example, although it is true that the environmental conditions surrounding two vehicles involved in a given accident will almost always be the same, the roadway conditions could be different—e.g., two vehicles approaching an intersection on different roads. Therefore, if there is interest in the two separate vehicles, a roadway cross-section for each can be prepared.

Major emphasis in the vehicle section is given to establishing the maintenance condition and modifications to original equipment. The identification of the vehicle (except for tires) is already given in the parent CPIR form. The emphasis on maintenance and modifications is not for the purpose of attributing accident causation to these factors; rather, the purpose is to assess their influence, if any, on the "as-new" handling qualities of the vehicle.

There is considerable evidence suggesting that the operator is a large, if not the major, factor in accident causation. Further, it has been shown that driver age and sex are two characteristics that correlate with accident experience. However, the specific qualities that make driver age and sex important have never been pinpointed with precision. For example, is it physical strength, stature, mental attitude, experience, maturity, and combinations thereof, or are there other driver qualities which make age and sex correlate with accident experience? Or is driver-vehicle matching a factor? Are young people more involved in accidents because they drive more Volkswagens or are Volkswagens more involved in accidents because they are driven more by young people? Whatever the case (if indeed there is a connection), pinpointing the answer will require that more information be gathered about driver characteristics than has typically been the case. The driver section of the supplement has been developed with this point of view. The specific information to be collected includes body dimensions, physical strength measurements, reaction times, vision performance, physical condition, academic education, driver education, driving experience, and familiarity with the area, among other variables.

In the accident kinematics section, the emphasis is on a careful analysis of skid marks. This section can be expanded to several pages for any number of skid marks with each skid mark and its causative tire being serially identified. Space is allotted for denoting the vehicle motions and driver actions that seemingly correlate with the skid mark information. The information is again supplemental to the CPIR form with the objective of assisting the reconstruction of the accident either manually or by means of computer simulation.

In general, the philosophy adopted in developing the Vehicle Handling Supplement was that of including every variable that could either be directly related to a vehicle handling factor or could confound an analysis seeking to establish the influence of handling.

BLANK

9.0 A DETERMINISTIC METHODOLOGY

The analytical methodology described in previous sections of this report is based on the use of statistical inference as a means of determining the role of vehicle handling in accident causation. Clearly, a statistical approach is but one of several ways in which insight can be developed in understanding this complex and very difficult cause/effect relationship. For example, Prentice [55] has shown that Game Theory can be used as a tool in optimizing driver strategies in car-to-car accident avoidance. Further, Rice [56] has developed methods of comparing actual car/driver performance with performance that is theoretically available through the use of what he has called a g-g diagram.

In this section of the report, a different approach is taken towards evaluating the accident avoidance capabilities of a vehicle/driver system as a means of supplementing the findings to be drawn using the tools of statistical inference. The approach is an adaptation of the pursuit-evasion analysis methods which have been developed as a means of evaluating air-to-air combat weapons systems. In the military context, the objective of an attack by an air-to-air missile is to get as close as possible to a target aircraft before its warhead is detonated. A measure of the effectiveness of the missile, then, is the magnitude of the closest approach, or miss distance, that the missile can achieve under a given set of attack conditions. Changes in the design of the missile (or in launch tactics, guidance strategies, control laws, etc.) can be evaluated (usually through simulation techniques) by noting the effect of such changes on the miss distance.

In an accident avoidance scenario involving autombiles, the situation is just the opposite with respect to miss distance. A better performing car in an accident avoidance context is one that is able to increase the miss distance relative to that of a competing design. Further, a necessary requirement following the initial accident avoidance maneuver is that the automobiles carry out a safe recovery phase. It does little good to avoid an errant vehicle in the right lane by maneuvering into the left lane and striking an oncoming vehicle. It is clear, then, that there are both similarities and differences in relating accident avoidance in the highway context to that of attack tactics in air-to-air combat. The situations are similar enough, however, such that the possible benefits achievable in applying pursuit-evasion analysis to accident avoidance are of considerable interest.

The discussion here will consist of (1) the presentation of a simple mathematical model describing the differential geometry of two vehicles involved in accident avoidance, (2) the application of the model to the simulation of a single accident avoidance scenario, and (3) the manipulation of the simulation results into a form which can be used to show the influence of cornering capability on accident avoidance performance.

9.1 Differential Geometry

The angle and displacement conventions describing the horizontal motions of two vehicles involved in an accident avoidance situation are shown on Figure 9.1. The equations describing vehicle motion can be broken down into those describing relative motion and those describing absolute motion. The equations governing relative motion can be written as follows:

$$R = V_B \cos(\phi+\psi) + V_A \cos(\theta-\psi) \tag{9.1}$$

$$\dot{\psi} = V_B \sin(\phi+\psi) - V_A \sin(\theta-\psi) \tag{9.2}$$

$$\dot{x}_r = V_A \cos\theta + V_B \cos\phi \tag{9.3}$$

$$\dot{y}_r = V_A \sin\theta - V_B \sin\phi \tag{9.4}$$

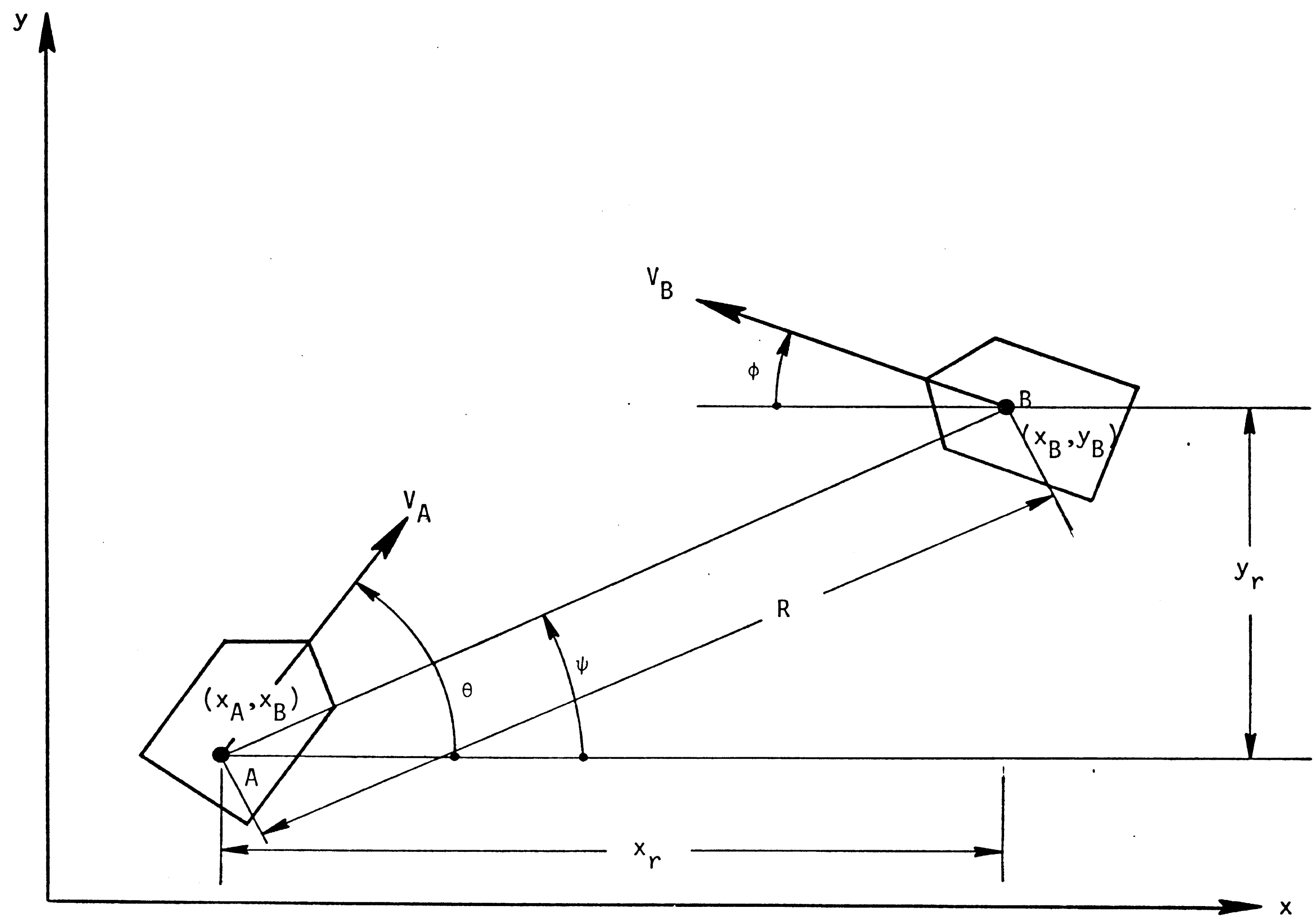


Figure 9.1 Geometry conventions

$$R = \int_{t_o}^{t_1} \dot{R}dt + R_o \tag{9.5}$$

$$\psi = \int_{t_o}^{t_1} \dot{\psi}dt + \psi_o \tag{9.6}$$

$$x_r = \int_{t_o}^{t_1} \dot{x}_r dt + x_{ro} \tag{9.7}$$

$$y_r = \int_{t_o}^{t_1} \dot{y}_r dt + y_{ro} \tag{9.8}$$

The absolute motion equations are given by:

$$\dot{V}_A = D_A \tag{9.9}$$

$$\dot{V}_B = D_B \tag{9.10}$$

$$\dot{\theta} = n_A/V_A \tag{9.11}$$

$$\dot{\phi} = n_B/V_B \tag{9.12}$$

$$\dot{x}_A = V_R \cos \theta \tag{9.13}$$

$$\dot{y}_A = V_A \sin \theta \tag{9.14}$$

$$V_A = \int_{t_o}^{t_1} D_A dt + V_{Ao} \tag{9.15}$$

$$V_B = \int_{t_o}^{t_1} D_B dt + V_{Bo} \tag{9.16}$$

$$\theta = \int_{t_o}^{t_1} \dot{\theta}dt + \theta_o \tag{9.17}$$

$$\phi = \int_{t_o}^{t_1} \dot{\phi}dt + \phi_o \tag{9.18}$$

$$x_A = \int_{t_o}^{t_1} \dot{x}_A dt + x_{Ao} \tag{9.19}$$

$$y_A = \int_{t_o}^{t_1} \dot{y}_A dt + y_{Ao} \tag{9.20}$$

$$x_B = x_A + x_r \tag{9.21}$$

$$y_B = y_A + y_r \tag{9.22}$$

The terms D_A and D_B represent the longitudinal accelerations applied to the A or B vehicle, respectively, along its velocity vector. Similarly, the terms n_A and n_B represent lateral accelerations applied normal to a velocity vector. The terms on the right side of Equations (9.5) to (9.8) and (9.15) to (9.20) with a zero subscript are quantities constituting initial conditions.

9.2 Application

The above equations, programmed into a digital computer to comprise a simulation model, were used to evaluate the accident scenario diagrammed at the top of Figure 9.2. The scenario represents a situation in which vehicle A, traveling in the right lane, is confronted by a second vehicle, B, traveling in the opposite direction and which has crossed over into A's lane of travel. A is initially traveling at 45 mph and is pointed at an angle of 10° toward the right pavement edge. B is traveling at 60 mph and is

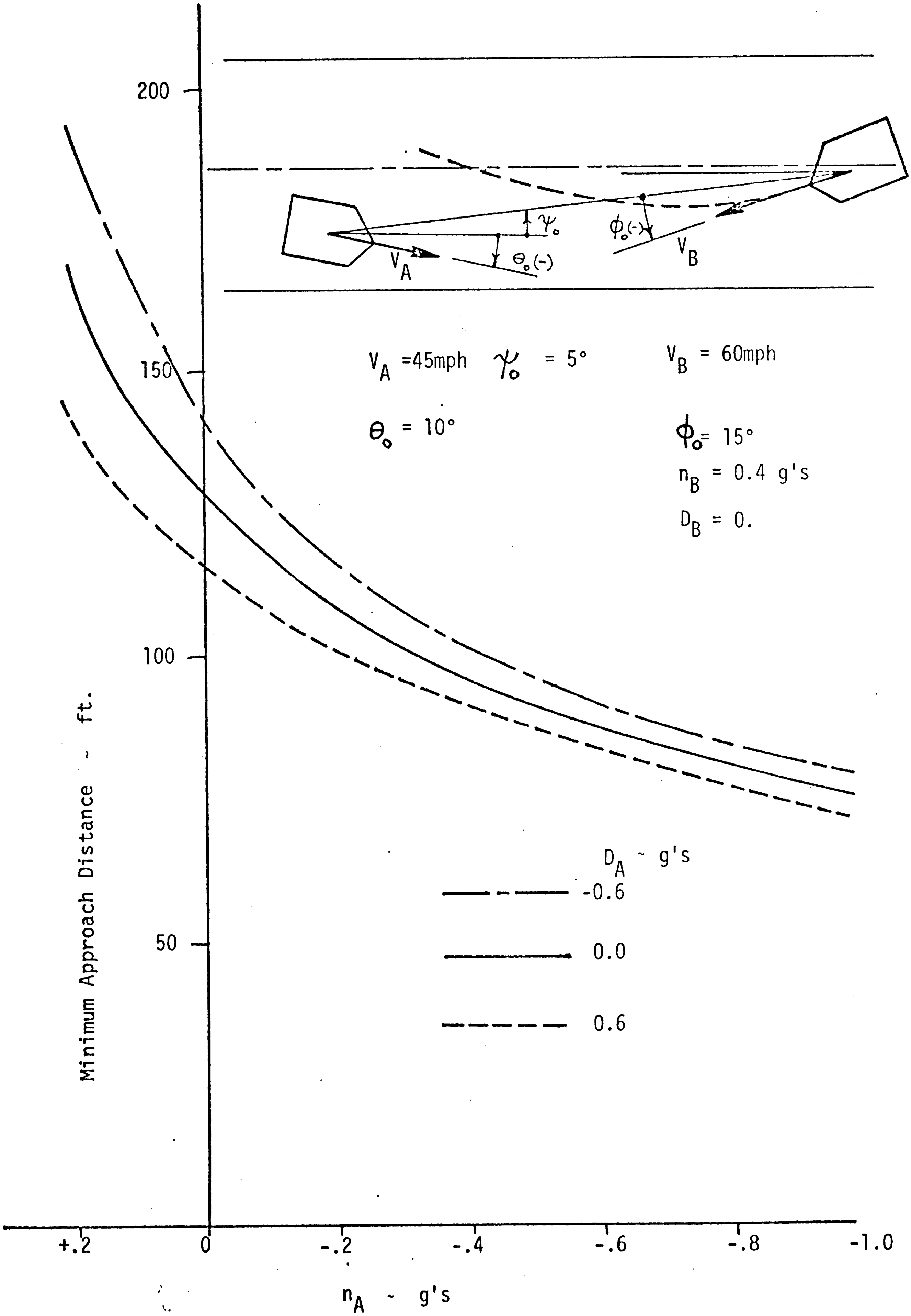


Figure 9.2. An accident avoidance performance example.

also pointing at the right pavement edge (i.e., with respect to A's direction of travel), but at an angle of 15°. Further, at the point at which the simulation is initiated, B is in the process of making a 0.4 g cornering maneuver back into his own lane. B chooses only to steer during this maneuver and does not brake or accelerate.

With these initial conditions constituting the assumed accident scenario, a series of simulation runs were made in which vehicle A attempts to avoid B (B's maneuver remains fixed). A's avoidance capabilities are illustrated by the three curves on Figure 9.2 which represent different combinations of avoidance tactics. The ordinate on Figure 9.2 is the Minimum Approach Distance that A can be from B and still avoid a collision. Obviously, the closer A could be to B, and avoid a collision, the better are A's capabilities in accident avoidance, i.e., the longer the driver of A could wait before executing an avoidance maneuver.

The three curves on Figure 9.2 show this Minimum Approach Distance as a function of the lateral acceleration, n_A, that A uses in its avoidance maneuver. A negative value of n_A means that vehicle A turns to its right and vice versa. As would be expected, it is clear that a maneuver to the right by A (countering a maneuver to its right by B) is the best strategy, and that larger values of lateral acceleration in the maneuver allow for a closer approach (i.e., smaller values of Minimum Approach Distance) before the maneuver is initiated. Perhaps not quite so apparent is the influence of braking or acceleration on accident avoidance performance.

On Figure 9.2, the upper curve is for 0.6 g's of braking, the lower curve is for 0.6 g's of acceleration and the middle curve represents no braking or accelerative action. It is apparent from the point of view of accident avoidance that in this scenario acceleration is preferable to braking. If vehicle A accelerates, it is able to move out of the path of vehicle B more rapidly. Braking, on the other hand, causes vehicle A to linger in the path of vehicle B a bit longer. In this particular scenario, accelerating while cornering to the right is the optimum maneuver to avoid an accident. If an impact does occur, however, the severity of the impact would undoubtedly be greater if an accelerative tactic were employed. Further, if an accident was avoided by using an accelerative maneuver, the subsequent recovery maneuver very probably would also be more difficult.

Regardless of what longitudinal maneuver (braking, accelerating, or none) is employed, however, it is quite apparent that a cornering maneuver has a far greater influence on the outcome. This result is intuitively apparent when one notes that a lateral displacement of seven to ten feet is enough to avoid an accident while a longitudinal distance of upwards of eighty feet is necessary to come to a full stop from 45 mph by applying the brakes. The factors that apparently inhibit drivers from using lateral maneuvers more frequently in accident avoidance (Reference 57 shows that 19.5% of drivers involved in accidents employ braking before the impact while only 9.0% employ steering) undoubtedly stem from the unknown dangers of the recovery phase, i.e., either getting off the road or into the opposing lane of traffic.

9.3 Cornering Performance Versus Accident Avoidance Performance

One of the benefits that derive from the above kind of analysis is an understanding of how changes in vehicle handling performance influence accident avoidance performance. As noted in the previous subsection, the Minimum Approach Distance, as shown on the ordinate of Figure 9.2, is a measure of accident avoidance performance, while vehicle lateral acceleration performance (or cornering capability), the abscissa on Figure 9.2, is one measure of vehicle handling performance. By examining this relationship, it becomes possible to answer the very intriguing question,

> "How does a 10% improvement in cornering performance influence a vehicle's potential ability to avoid an accident?"

The answer can be sought from a plot like that shown on Figure 9.3. The lower curve on Figure 9.3 shows the percent improvement in accident avoidance performance (as measured by the Minimum Approach Distance on Figure 9.2) as a function of 0.2 g incremental changes in lateral acceleration performance. The upper curve is a plot of the percent change in the abscissa scale as 0.2 g's of lateral acceleration capability are added, e.g., the rightmost point on the abscissa scale—indicating a design change that would improve the lateral acceleration capability of a vehicle from 0.8 g's to 1.0 g's—represents a 25% improvement in cornering performance, i.e., 100 x (1.0-0.8)/0.8.

On comparing the upper curve with the lower curve, it will be noted that improving the lateral acceleration performance of a vehicle from 0.6 g's to 0.8 g's—a 33% increase—results in only an 8% increase in accident avoidance performance. The respective costs associated with increasing cornering capability (improvements in tires, suspensions, road surfaces, driver skills, etc.) and benefits accruing from reduced accident experience have not been computed, but it is clear that such exercises could be undertaken.

9.4 Summary

It cannot be argued that the mathematical model employed here involves many simplifying assumptions. No attempt, for example, has been made to account for the complicated handling performance of a vehicle as it approaches its limit maneuvering regime. Neither has any consideration been given to the manner in which braking action limits a vehicle's ability to corner. However, there is no reason why such refinements could not be added within the basic framework described above. Clearly, a full-fledged vehicle dynamics simulation could be employed. Accordingly, a potential exists for investigating the influence of any specific handling property on the accident avoidance performance of a motor vehicle. Further, it is possible to add driver influences (reaction time, control force

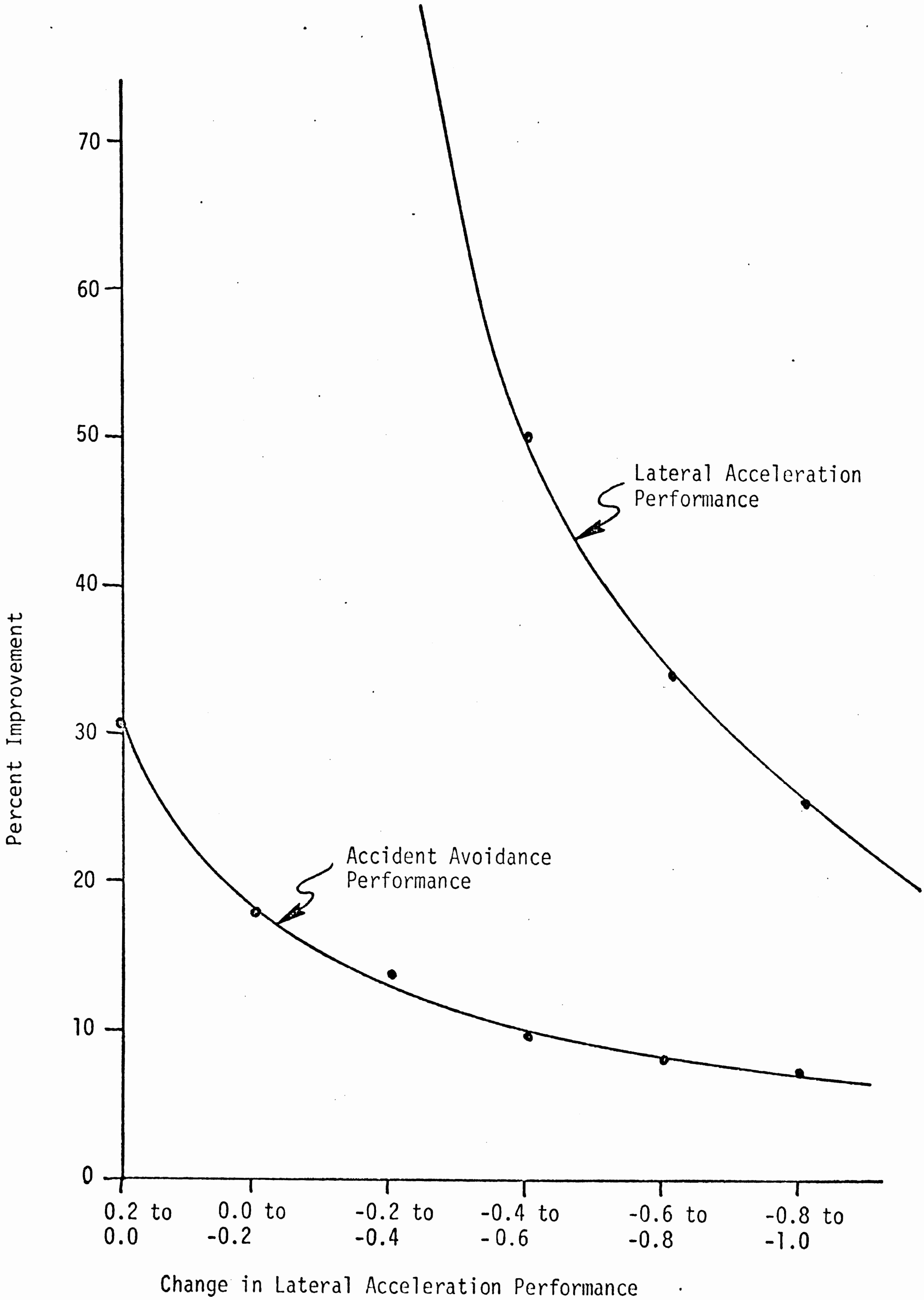


Figure 9.3. Accident avoidance performance versus lateral acceleration performance.

limitations, maneuver actions, etc.) and roadway influences (surface skid resistance, geometric features, roughness, etc.) to this approach. Although not a panacea, pursuit-evasion methods represent a deterministic approach for examining the role of vehicle handling in collision or accident causation, as opposed to examining, on a statistical basis, factors which may be deemed to be causative or contributory to the accident record. Given the complexity and elusiveness of the issue, it could be argued that both approaches could and should be pursued in parallel.

BLANK

10.0 CONCLUSION

The primary findings from the research performed in this study constitute a statistical analysis methodology applicable to the determination of the role of vehicle handling in accident causation. Secondary findings consist of (1) an indepth accident reconstruction methodology which can be applied to the pre-crash accident phase—that phase where vehicle handling factors are important—and (2) a deterministic methodology which can be applied to assess vehicle handling performance in terms of accident avoidance performance.

There is ample evidence to show that American passenger cars exhibit a wide range of handling performance characteristics. While many handling properties have been hypothesized as having a link to accident causation, the literature reviewed in the context of this study is virtually devoid of any defensible supporting evidence. There are many reasons for this state of affairs. One of the prime difficulties is the driver's ability to adapt to wide variations in vehicle handling performance. Through adaptation, the driver can make what might be considered a poor handling vehicle perform reasonably effectively. Another major difficulty derives from the myriad of confounding factors, not directly related to the vehicle, which make every accident unique. If accident causative factors related to vehicle handling are to be distilled from the accident record, the influences of non-vehicle factors must be taken into account.

The statistical analysis methodology presented in Section 7 was specifically developed for determining whether vehicle handling-related factors, as can be hypothesized to play a role in the accident process, are, in fact, involved. It was concluded that the needed methodology requires the existence and use of four kinds of data, viz.:

1. Vehicle Exposure to Risk Data

2. Accident Data

3. Vehicle Handling Data, and possibly

4. Vehicle Image Risk Data

In each case, the data that must be collected are either unique or have never before been collected in the quantity and detail that appears to be required.

This circumstance results from the level of refinement of the questions which must be answered in order to link vehicle handling performance to accident experience. Merely determining which vehicle makes and models have the highest accident rates will not produce definitive or sufficient conclusions. Ultimately, answers must be obtained to questions such as:

> "What is the relationship between different levels of understeer and accident rates on curves during wet weather, given that the rates for each level of understeer being examined are normalized for (1) driver population variables, (2) exposure to risk variables, and (3) image risk variables?"

The study has shown that the determination of statistically significant answers to questions of this level of refinement requires data of unprecedented detail and quantity.

It is generally acknowledged that exposure to risk data is needed to normalize accident data so as to yield accident rates, i.e., accidents per mile traveled. However, the type of miles driven, the kind of driver, the environmental conditions, etc. (i.e., the operating risk to which a vehicle has been exposed) should be accounted for in a normalizing process. Further, it appears that exposure to risk data has never been collected before where the type of vehicle driven has been specifically identified along with the conditions of operating risk.

Collecting exposure to risk data will be much more expensive than collecting accident data by routine police-reporting methods since structured interviews or surveys must be carried out.

The study has indicated that a minimum of 300,000 accident cases will be required to draw conclusions about vehicle handling factors. This number is not firm (i.e., more could very well be needed), since the actual number of cases will depend upon the level of complexity of the questions posed and the desired confidence in the resulting answers. The accident cases should be limited to a selected number of vehicles (approximately 100) for which handling data are available or otherwise obtained. The accident data need not be of the level of the investigative detail used in MDAI, but should be more accurate and contain more detail than is the case in police reporting. Because of the large number of cases required, it is recommended that the data be collected through police agencies that have been oriented to the importance of accuracy and thoroughness.

Vehicle handling data must be derived from measurements of new vehicles and should include both <u>normal</u> and <u>limit</u> handling performance indices. These performance indices will constitute the "independent variables" in correlation and regression analyses carried out to identify links with accident rate descriptors—the "dependent variables." The 100-vehicle sample should represent a wide cross-section of vehicle characteristics and, in addition, should be well represented in the vehicle population existing within the geographical area in which the accident and exposure data are to be collected. Collecting handling data on such a large number of vehicles will unquestionably be a formidable and expensive undertaking.

It is recommended that vehicle image risk data also be acquired. These data would be used to account for "image" factors which may cause the same individual driver to drive one vehicle (say, a standard sedan) in a prudent manner and another (say, a sports car) in a decidedly risky manner. Consistent differences in driving patterns could account for differences in accident rates. Sports cars as a general class seem to be more involved in accidents than conventional passenger cars even though the former are almost universally considered to have better handling characteristics than the latter.

Because of the related use to which the various sets of data are to be applied, it is recommended that accident, exposure to risk, and image risk data all be collected within a two-year period and in the same designated geographic area.

In addition to the major effort directed towards the development of a statistical approach for determining the role of vehicle handling in accident causation, tools were also developed to assist in assessing the influence of vehicle handling factors in individual accidents. Such a clinical approach requires that the investigator attempt to reconstruct the pre-crash phase of an accident—that phase where vehicle handling factors will appear if indeed such are present. Since available reconstruction methodologies fall short in being able to completely define the pre-crash actions of the driver and the resulting velocity and acceleration components of the vehicle, efforts were directed specifically towards the development of those facets of a reconstruction methodology that, when applied, should substantially increase the information available concerning vehicle handling as an accident causative factor.

As indicated in this report, the complexity of the overall problem prompted the application of pursuit-evasion tactics of Game Theory to accident avoidance scenarios with the objective of gaining additional insight. Methods were demonstrated for showing how vehicle handling performance can be directly compared with accident avoidance performance through a vehicle handling simulation model. The work presented herein is embryonic, however, and needs to be developed further with vehicle, driver, and roadway representations that are considerably more realistic than those employed in this preliminary exercise.

In closing, the use of a statistical approach in determining the role of vehicle handling in accident causation calls for collecting and analyzing several types of data in unprecedented amounts. Implementing the program will be a formidable and costly undertaking. Pressures will undoubtedly arise for reducing the scope of the program recommended herein as a means of answering the questions of interest. Certainly there is nothing wrong with reducing scope and costs—provided the eventual objectives are not jeopardized. A good deal of care should therefore be exercised before making any decisions to reduce segments of the proposed program. The consequences of collecting fewer data elements in terms of reduced confidence in results can be clearly established through the methods developed in Section 7.

Although the recommended program will be costly to implement, there are supplementary benefits that should be carefully considered. Much of the derived data (having the form recommended here) will be applicable to studying and confirming hypotheses not necessarily related to vehicle handling. In particular, the accident and exposure-to-risk data plus a few additional data elements in each collection program, could very well provide very useful information. After all, at this point in time, truly valid exposure-to-risk data is virtually non-existent. Consequently, valid accident rate information is also virtually non-existent. It would therefore be worthwhile to consider the utility of the data to be derived from research investigating the role of vehicle handling factors in terms of studying the influence and role of other factors and to plan the collection task accordingly.

BLANK

11.0 REFERENCES

1. Jones, I.S., "Car Characteristics: Their Contribution to Accident Risk," Preprint A106, Seventh Australian Road Research Board Conference, Adelaide, 1974.

2. Reinfurt, D.W. and Campbell, B.J., Mileage Crash Rates for Certain Car Make and Model Year Combinations: A Preliminary Study, Highway Safety Research Center, The University of North Carolina, December 1974.

3. Wright, P.H., ed., Reducing Highway Deaths and Injuries, Reducing Highway Deaths and Injuries Seminar, Atlanta, Ga., March 19-22, 1972.

4. Snively, G.G., Phillips, R.M., and Nielsen, G.L., "Causal Factors in Single-Vehicle Accidents," paper presented at the Meeting of the American Association for Automotive Medicine, 1966.

5. Penn, H.S., "Causes and Characteristics of Single-Car Accidents: Part I," Highway Research Record, No. 79, 1965.

6. Bohlin, N., Ljungström, G., and Nordström, O., Skid Accident Analysis. Summary Report, Report No. 2-03, Swedish ESV Program, February 1973.

7. Goddard, J.L. and Haddon, W., Jr., "An Introduction to the Discussion of the Vehicle in Relation to Highway Safety," Passenger Car Design and Highway Safety, Consumers Union of U.S., Inc., 1962.

8. Kennedy, R.J., "Reducing the Frequency of Highway Collisions," Engineering Journal, Vol. 55, September, 1972.

9. Treat, J.R. and Joscelyn, K.B., "The Role of Steering and Suspension Degradations and Failures in Accident Causation," SAE Paper #740150, Automotive Engineering Congress, Detroit, February 1974.

10. Bundorf, R.T., "Driver Vehicle Control Performance," Automotive Safety Engineering Seminar Proceedings, Milford, Mich., 1973.

11. Treat, J.R. and Joscelyn, K.B., "Results of a Study to Determine Accident Causes," SAE Paper #730230, International Automotive Engineering Congress, Detroit, January 1973.

12. Jones, G., "Factors Leading to Loss of Control—A Guide for Accident Investigations," International Technical Conference on Experimental Safety Vehicles, London, June 1974.

13. Grime, G., "Research on Skidding in the United Kingdom," In-Depth Study Reports from the World Survey of Current Research and Development on Roads and Road Transport, U.S. Government Printing Office, Washington, D.C., June 1973

14. Grime, G., "Importance of Loss of Directional Control in Car Accidents," Control of Vehicles During Braking and Cornering Symposium Proceedings, Institution of Mechanical Engineers, 1963.

15. A Second Study of Relationships Between Tire Tread Depth and the Likelihood of Accident Involvement, Highway Safety Foundation, Mansfield, Ohio, May 1972.

16. Single-Vehicle Accidents: A Summary of Research Findings, Automotive Safety Foundation, Washington, D.C., 1968.

17. Shapiro, S.S. and Tourin, B., Vehicle Design Elements Affecting Traffic Safety—Special Interim Report, New York State Department of Motor Vehicles, Albany, 1969.

18. Compact Car Accident Study. Garden State Parkway, 1969, New Jersey Highway Authority, Woodbridge, N.J., 1969.

19. Case, H.W., Burg, A., and Baird, J.D., Accident Frequency as Related to Vehicle Size, Institute of Transportation and Traffic Engineering, California University, Los Angeles, August 1972.

20. Hart, S., "Big Cars - Safer for Whom?", International Congress on Automotive Safety. Third. Proceedings, Vol. II, U.S. Government Printing Office, Washington, D.C., 1974.

21. Milie, P.L., An Analysis of Accidents in New York State by Make of Vehicle. Final Report, Report No. DOT/HS 800 735, New York State Department of Motor Vehicles, Albany, June 1972.

22. Negri, D.B., Front Versus Rear Engine Automobiles, Report No. FH-11-6799-1, New York State Department of Motor Vehicles, Albany, March 1972.

23. Hoffman, E.R., "An Evaluation of Measures to Reduce Accident Occurrence," National Road Safety Symposium. Papers Presented, Canberra, Australia, 1972.

24. Schreiber, R.J., Accident-Inducing Characteristics of Motor Vehicles, Progress Report, Public Service Research, Inc., Stamford, Conn., March 1961.

25. Evaluation of Motor Vehicle Safety Standards. Final Report, Report No. 4135-496/DOT/HS 801 012, Center for the Environment and Man, Inc., Hartford, Conn., December 1973.

26. Mela, D.F. and Ponce, P.V., "An Analysis of Pinto and Vega Accident Involvement Frequencies in the State of Massachusetts," Technical Note N43-31-1, NHTSA, Washington, D.C., June 1973.

27. Giles, C.G. and Sabey, B.E., "Skidding as a Factor in Accidents on the Roads of Great Britain," Skid Prevention Convention. First International. Proceedings, Part I., Virginia, August 1959.

28. Tchelet, M., "A Study of the Relationship Between Certain Vehicle Characteristics and Accidents," Master's Thesis, New South Wales University, Kensington, Australia, January 1962.

29. Mackay, G.M., Causes and Effects of Road Accidents. Part III- the Vehicles, Birmingham University, England, June 1969.

30. Jones, I.S., The Use of Accident Analysis in Improving Vehicle Design to Prevent Accidents, University College of London, Report No. J26, June 1972.

31. Jones, I.S., "Vehicle Stability Related to Frequency of Overturning for Different Models of Cars," Preprint A99, Seventh Australian Road Research Board Conference, Adelaide, 1974.

32. Limpert, R. and Gamero, F.E., "The Accident Avoidance Potential of the Motor Vehicle: Accident Data, Vehicle Handling and Safety Standards," International Congress on Automotive Safety. Third. Proceedings, Volume II, U.S. Government Printing Office, Washington, D.C., 1974.

33. Foldvary, L.A. and Potter, D.W., "Accident Risk Associated with Design Characteristics of the Car," Paper No. 641, Fifth Australian Road Research Board Conference, Melbourne, 1970.

34. Memo from M. Huber to D. Dunlap, "Vehicle Handling," Highway Safety Research Institute, January 28, 1975.

35. Ervin, R.D., Grote, P., Fancher, P.S., MacAdam, C.C., and Segel, L., Vehicle Handling Performance, Highway Safety Research Institute, Univ. of Michigan, Ann Arbor, 1972.

36. "MVMA Specification Form - Passenger Car," Available for United States passenger cars from 1969 forward.

37. Rasmussen, R.E., Hill, F.W., and Riede, P.M., "Typical Vehicle Parameters for Dynamics Studies," General Motors Proving Ground Publication No. A-2542, April 1970.

38. Koiter, W.T. and Pacejka, H.B., "Skidding of Vehicles Due to Locked Wheels," Proc. Inst. Mech. Engrs., Vol. 183, Pt. 3H, 1968, pp. 3-18.

39. Fleiss, J.L., Statistical Methods for Rates and Proportions, John Wiley, New York, 1973.

40. Carroll, P.S., et al., Acquisition of Information on Exposure and on Non-Fatal Crashes, Report 03169, Vols. I-VI, Highway Safety Research Inst., Univ. of Michigan, Ann Arbor, May 1971.

41. Accident Analysis and Prevention, Special Issue on Exposure to Accidents, Vol. 5, No. 2, June 1973.

42. Carlson, W.L., Sampling from Sequential Populations, Ph.D. Thesis, University of Michigan, 1973.

43. Ervin, R.D., Grote, P., Fancher, P.S., MacAdam, C.C., and Segel, L., Vehicle Handling Performance. Summary Report, Highway Safety Research Inst., Univ. of Michigan, Ann Arbor, November 1972.

44. Dugoff, H., Ervin, R.D., and Segel, L., Vehicle Handling Test Procedures, Highway Safety Research Inst., Univ. of Michigan, Ann Arbor, Report No. PF-100, November 1970.

45. Fancher, P.S., Ervin, R.D., Grote, P., MacAdam, C.C., and Segel, L., Limit Handling Performance as Influenced by Degradation of Steering and Suspension Systems. Vol. I, Highway Safety Research Institute, Univ. of Michigan, Report No. UM-HSRI-PF-72-3-1, November 1972.

46. Myers, R.H. and Ottman, M.F., Jr., A Description of the ORBUS III System and Its Legal Aspects, Vaught Missiles and Space Co., Dallas, Texas, 1972.

47. Baker, J. S., Traffic Accident Investigation Manual, The Traffic Institute, Northwestern University, 1975.

48. Schonfeld, R., Skid Numbers from Stereo-Photographs, Department of Highways, Ontario, D.H.O. Report No. RR155, January 1970.

49. Schonfeld, R., "Photo-Interpretation of Pavement Skid Resistance in Practice," Transportation Research Board, No. 523, 1974.

50. Howerter, E.D. and Rudd, T.J., "Automation of the Schonfeld Method for Highway Surface Texture Classification," presented at the 55th Annual Meeting of the Transportation Research Board, January 1976.

51. Standard Method of Test for Skid Resistance of Paved Surfaces Using a Full-Scale Tire, ASTM E 274-70, American Society for Testing and Materials, 1970.

52. Standard Specification for Standard Tire for Pavement Skid Resistance Tests, ASTM E 501-73, American Society for Testing and Materials, 1973.

53. Segel, L., "Tire Traction on Dry Uncontaminated Surfaces," The Physics of Tire Traction, Hays, D.F. and Browne, A.L., Eds., Plenum Press, New York, 1974.

54. Mortimer, R.G., Segel, L., Dugoff, H., Campbell, J.D., Jorgeson, C.M., and Murphy, R.W., Brake Force Requirement Study: Driver-Vehicle Braking Performance as a Function of Brake System Design Variables, Highway Safety Research Institute, Univ. of Michigan, Contract No. FH-11-6952, April 10, 1970.

55. Prentice, J.W., "The Evasive Action Decision in an Intersection Accident: A Game Theory Approach," Journal of Safety Research, Vol. 6, No. 4, December 1974.

56. Rice, R.S., "Measuring Car-Driver Interaction with the g-g Diagram," SAE Paper #730018, January 1973.

57. Limpert, R., "An Investigation of Braking and Steering in Motor Vehicle Accidents," SAE Preprint 760346, presented at the 1976 Automotive Engineering Congress and Exposition, Detroit, Mich., February 23-27, 1976.

58. Performance Data: New 1973 Passenger Cars and Motorcycles, Compiled from Data Furnished by Vehicle Manufacturers, NHTSA, Washington, D.C., November 1972.

59. Lister, R.D., "Some Problems of Emergency Braking in Road Vehicles," Control of Vehicles During Braking and Cornering. Symposium Proceedings, IME, England, 1963.

60. Experimental Safety Vehicle Tradeoff and Integration Systems Studies. Vol. II, American Machine and Foundry Company, California, September 1973.

61. Okada, T., Takiguchi, T., Nishioka, M., and Utsonomiya, G., "Evaluation of Vehicle Handling and Stability by Computer Simulation at the First Stage of Vehicle Planning," SAE Paper #730525, Automobile Engineering Meeting, Detroit, Mich., May 1973.

62. "Volvo Presentations at the Fourth International Experimental Safety Vehicle Conference," International Technical Conference on Experimental Safety Vehicles, Kyoto, Japan, March 1973.

63. Schiappati, A., "Active Safety. A Contribution to the Study of the Vehicle-Driver System," International Technical Conference on Experimental Safety Vehicles, Third Report, U. S. Government Printing Office, Washington, D.C., 1972.

64. McKibben, J., Gray, C., and Niemiec, K., State-of-the-Art Definition of Vehicle Handling. Vol. I. Final Report, Digitek Corp., Report No. FH-11-7315-DARD-1/HS 800 465, April 1970.

65. Jacobson, M.A., "The Punctured Pneumatic Tyre from the User's Viewpoint," International Technical Conference on Experimental Safety Vehicles, London, June 1974.

66. Ervin, R.D., "Experimentation in Open-Loop Response Utilizing an Automatic Vehicle Controller," Joint Automatic Control Conference, Austin, Texas, June 1974.

67. Janeway, R.N., "Vehicle Design Aspects of Safe Handling," Passenger Car Design and Highway Safety, Consumers Union of U.S., Inc., 1962.

68. Maximum Safe Speed for Motor Vehicles, National Highway Safety Bureau, Government Printing Office, Washington, D.C., January 1969.

69. Jones, G., "Vehicle Handling," International Technical Conference on Experimental Safety Vehicles. Third, U.S. Government Printing Office, Washington, D.C., 1972.

70. Bergman, W., "Measurement and Subjective Evaluation of Vehicle Handling," SAE Paper #730492, Automobile Engineering Meeting, Detroit, May 1973.

71. Segel, L., "Vehicle Handling Research and Its Influence on U.S. Automotive Engineering Practice," Passenger Car Design and Highway Safety, Consumers Union of U.S., Inc., 1962.

72. McCaffrey, G.F.W., "Motor Vehicle Safety: the Vehicle," Technical Note No. 4, National Research Council, Ottawa, Canada, May 1966.

73. Orme, J.S., Perring, H., and Paisley, J.L., "The Factors Contributing to the Accidents: Roads, Vehicles, People," Road Accidents, Road Accidents Convention, England, November 1965.

74. Muckler, F.A. and Obermayer, R.W., "The Human Operator," International Science & Technology, July 1964.

75. Sullivan, D.J. and Meister, D., "Human Factors in Driver Research," Pre-Crash Factors in Traffic Safety, The American Association of Automotive Medicine, 12th Annual Symposium, 1968.

76. Hansman, F.S., "The Driver in Relation to the Physiological Limitations Imposed on Him as a Human Being," The Medical Journal of Australia, July 4, 1959.

77. Platt, F.N., "Operations Research on Driver Behavior," Traffic Engineering , September 1961.

78. Stoudt, H.W., Human Engineering and Automotive Design: Report of a Workshop Held at the General Motors Technical Center, Harvard School of Public Health, Boston, Mass., 1959.

79. McFarland, R.A., Damon, A., Stoudt, H.W., Moseley, A.L., Dunlap, J.W., and Hall, W.A., Human Body Size and Capabilities in the Design and Operation of Vehicular Equipment, Harvard School of Public Health, Boston, Mass., 1953.

80. Alexander, G.J. and Lunenfeld, H., Positive Guidance in Traffic Control, U. S. Department of Transportation, April 1975.

81. McRuer, D.T. and Krendel, E.S., "The Human Operator as a Servo System Element," Journal of the Franklin Institute, 267, 1959.

82. Sheridan, T.B. and Ferrell, W.R., Man-Machine Systems: Information, Control and Decision Models of Human Performance, The MIT Press, Cambridge, Mass., 1974.

83. Clement, W.F., Allen, R.W., and Jex, H.R., Experiments in Controlled Display Scanning and Sampling, Systems Technology, Inc., Technical Report 170-2, 1969.

84. McRuer, D.T., Graham, D., and Krendel, E.S., "Manual Control of Single-Loop Systems," Journal of the Franklin Institute, 283, 1967.

85. Stapleford, R.L., Craig, S.J., and Tennant, J.A., Measurement of Pilot Describing Functions in Single-Controller Multi-loop Tasks, NASA CR-1238, 1969.

86. Gordon, D.A., "Experimental Isolation of Drivers' Visual Input," Public Roads, 33, 1966.

87. Dunlap, D.F., "Remote Steering of a Lunar Surface Vehicle," presented at the Michigan Navigation Conference, Institute of Navigation, Ann Arbor, Mich., June 1962.

88. McRuer, D.T. and Krendel, E.S., Dynamic Response of Human Operators, WADC-TR-56-524, U.S. Air Force, 1957.

89. Bekey, G.A., "The Human Operator as a Sampled Data System," IRE Trans. Human Factors in Electronics, HFE-3, 1962.

90. Lemay, L.P. and Westcott, J.H., "The Simulation of Human Operator Tracking Using an Intermittent Model," Proc. IEEE Symp. Human Factors in Electronics, Long Beach, Calif., 1962.

91. Young, L.R. and Stark, L., "Variable Feedback Experiments Testing a Sampled Data Model for Eye Tracking Movements," IEEE Trans. Human Factors in Electronics, HFE-4, No. 1, 1963.

92. Elkind, J.I., Kelley, J.A., and Payne, R.A., "Adaptive Characteristics of the Human Controller in Systems Having Complex Dynamics," Proc. 5th Annual IEEE Symp. Human Factors in Electronics, San Diego, Calif., 1964.

93. Costello, R.G., "The Surge Model of the Well-Trained Human Operator in Simple Manual Control," IEEE Trans. Man-Machine Systems, MMS-9, No. 1, 1968.

94. Kreifeldt, J.G., "A Sampled-Data Pursuit Tracking Model," IEEE Trans. Human Factors in Electronics, HFE-6, No. 1, 1965.

95. Pitkin, E.T., "A Nonlinear Feedback Model for Tracking Studies," Proc. 8th Annual Conf. on Manual Control, AFFDL-TR-72-92, Wright-Patterson AFB, 1972.

96. Johannsen, G., "Development and Optimization of a Nonlinear Multiparameter Human Operator Model," IEEE Trans. Systems, Man, and Cybernetics, SMC-2, No. 4, 1972.

97. Weir, D.H. and McRuer, D.T., "A Theory for Driver Steering Control of Motor Vehicles," Highway Research Record 247, 1968.

98. Gibson, J.J., The Perception of the Visual World, Houghton Mifflin, Boston, 1950.

99. Calvert, E.S., "Visual Judgments in Motion," Journal of the Institute of Navigation, 7, 1957.

100. Schmidt, I. and Connolly, P.L., "Visual Considerations of Man, the Vehicle and the Highway," Soc. of Automotive Engineers, SAE SP-279, 1966.

101. Gordon, D.A., "Perceptual Basis of Vehicular Guidance," Public Roads, 34, 1966.

102. Hayes, G.G., Koppa, R.J., and White, J.T., Determination of Motor Vehicle Characteristics Affecting Driver Handling Performance, Texas Transportation Institute, 1975.

103. Wierwille, W.W., "Driving Simulator for Realistic Handling," Proc. of the Third International Conf. on Vehicle Systems Dynamics, Blacksburg, Va., 1974.

104. Yatabe, T. and Matsumoto, S., "Automobile Driving Simulator with Full Electronic Color Visual Display Device," XV Congres International, FISITA, Paris, 1974.

105. McRuer, D.T., Peters, R.A., Ringland, R.F., Allen, R.W., Blarevelt, A.A., and Weir, D.H., Driver Performance Measurement and Analysis System (DPMAS), Task 1: Requirements and Plans for Prototype Equipment, Systems Technology, Inc., 1974.

106. Anderson, P.A., Curtner, K.L., and Wolf, J.D., DRIVEM: Driver-Vehicle Interaction Effectiveness Model, Honeywell, Inc., 1975.

107. Gengenbach, W., "Experimental Investigation Into the Aquaplaning of Vehicle Tyres on Wet Roads," Automobil-Industrie, Vol. 12, No. 4, November 1967, pp. 74-79.

108. Moore, D. F., The Friction of Pneumatic Tyres, Elsevier Scientific Publishing Company, Amsterdam, 1975.

109. Staughton, G.C. and Williams, T., Tyre Performance in Wet Surface Conditions, RRL Report LR 355, Road Research Laboratory, Crowthorne, England, 1970.

110. Yeager, R.W. and Tuttle, J.L., "Testing and Analysis of Tire Hydroplaning," SAE Preprint 720471, Soc. of Automotive Engineers, May 1972.

111. Horne, W.B. and Dreher, R.C., Phenomena of Pneumatic Tire Hydroplaning, NASA TN-D-2056, National Aeronautics & Space Admin., Langley Research Center, November 1963.

112. Horne, W.B. and Joyner, U.T., "Pneumatic Tire Hydroplaning and Some Effects on Vehicle Performance," SAE 970C, 1965.

113. Besse, J., Water Film Thickness Effects on the Friction Between Tire and Pavement, NCHRP Project 1-12 (2), Pennsylvania State Univ., June 1972.

114. Kummer, H.W. and Meyer, W.E., Tentative Skid-Reistance Requirements for Main Rural Highways, National Cooperative Highway Research Program, Report 37, 1967.

115. Kummer, H.W., "Friction Between Tyre and Road," Interna. Colloquium on the Interrelation of Skidding Resistance and Traffic Safety on Wet Roads, Berlin, 1968.

116. Allbert, B.J. and Walker, J.C., "Tyre to Wet Road Friction at High Speeds," Inst. of Mech. Engrs., Automobile Div., Proc. 1965-66, Vol. 180, Part 2A, No. 4, 1966, pp. 105-121.

117. Galloway, B.M., Schiller, R.E., Jr., and Rose, J.D., The Effects of Rainfall Intensity, Pavement Cross Slope, Surface Texture, and Drainage Length on Pavement Water Depth, Texas Transportation Institute, Research Rept. No. 138-5, May 1971.

118. Dunlap, D.F., Fancher, P.S., Scott, R.E., MacAdam, C.C., and Segel, L., Influence of Combined Highway Grade and Horizontal Alignment on Skidding, Highway Safety Research Institute, Univ. of Michigan, Report UM-HSRI-PF-74-1, 1974.

119. Quinn, B.E. and DeVries, T.W., "Highway Characteristics as Related to Vehicle Performance," HRB Bulletin 250, 1960.

120. Quinn, B.E. and Thompson, D.R., "Effect of Pavement Condition on Dynamic Vehicle Reactions," HRB Bulletin 328, 1962.

121. Quinn, B.E. and Zable, J.L., "Evaluating Highway Elevation Power Spectra from Vehicle Performance," Highway Research Record, 121, 1966.

122. Yamakawa, S. and Kadono, I., "Road-Surface Undulation Models and Non-Linear Vehicle Suspension Models," XV Interna. Congress, FISITA, Paris, May 13-17, 1974.

123. BSI Proposals for Generalized Road Inputs to Vehicles, ISO/TC108/WG9 Document No. 5, 1972.

124. Brickman, A.D., Park, W.H., Wambold, J.C., and Zimmerman, J.R., Road Roughness Effects on Vehicle Performance, Report TTSC 7207, Pennsylvania State Univ., August 1972.

125. Quinn, B.E. and Hildebrand, S.E., "Effect of Road Roughness on Vehicle Steering," Highway Research Record, 471, 1973.

126. Schiappati, A., Active Safety. A Contribution to the Study of the Vehicle-Driver System. A First Approach to the Definition of an Undulation Surface for Road-Holding Tests, Report on the Third International Technical Conf. on Experimental Safety Vehicles, Washington, D.C., May 30-June 2, 1972.

127. Weber, K., "Are Men or Women Better Drivers," HIT Lab Reports, Vol. 5, No. 5, January 1975.

128. Highway Statistics 1970, U.S. Department of Transportation.

BLANK

APPENDIX A

SUPPLEMENTAL LITERATURE REVIEW

The literature reviewed in this section encompasses the role of vehicle handling in accident causation as it relates to:

a. Vehicle Performance Factors

b. The Vehicle/Driver Interface

c. The Vehicle/Roadway Interface

Another portion of the literature review is given in Section 4, where accident causation studies directly related to vehicle handling are discussed.

A.1 Vehicle Performance Factors

If it is presumed that "improvements" in vehicle performance can favorably influence the accident record, two questions arise:

a. What improvements are feasible?

b. How much improvement can be realized?

The main difficulty here, however, is in defining what constitutes an "improvement." Some performance indices, such as stopping distance (i.e., the smaller the better), would seemingly relate directly to improved safety. For others, e.g., understeer/oversteer, an optimum level is not immediately evident.

As a first step in determining whether a particular performance index has any bearing on safety, it would be good to know whether the values of that index vary significantly in the as-new vehicle population. If the variation is significant and the index indeed influences safety, then the influences of the index ought to show up in the accident record.

As is well known, new automobiles do vary widely in many handling performance indices. Some of these have been treated in the literature.

A.1.1 Braking Performance. Two aspects of braking performance are of interest with respect to accident avoidance: stopping performance and yaw stability. Stopping performance is easily compared by recording the distance it takes for a vehicle to stop from a given velocity on a known surface. Stopping distance is not the whole story, however, since it gives no indication of controllability. Thus, stopping distance while maintaining directional control is a more realistic criterion.

Data published annually by the National Highway Traffic Safety Administration [58] show that new passenger cars differ substantially in stopping distance capabilities. These reports contain stopping distances from 60 mph for lightly- and fully-loaded automobiles, as well as performance with power-assist systems inactive. Data for 1973 vehicles show that the range in stopping distances varies by 67% with fully operational systems, by over 150% with the partial failure of one subsystem (power brakes only), and by over 200% with total power brake unit failure (see Table A.1).

At the Highway Safety Research Institute of The University of Michigan, investigations of the limit braking performance of a sample of twelve different automobiles also found large variations in the responses [43]. In some cases the front wheels were found to lock first, while in others the rear wheels locked first. Premature rear wheel lockup usually introduced spin-out response. The vehicles generally exhibited a linear relationship between brake line pressure and average longitudinal deceleration when braked in a straight line, but the range in slope of this relationship varied by a factor of two for the several vehicles. Peak decelerations (without locking two wheels) ranged from approximately 0.7 g's to 0.9 g's among the twelve cars tested.

Table A.1. Braking Performance Data for 1973 Automobiles as Furnished by the Manufacturers: Stopping Distances from 60 mph.

(Extremes in each category marked)

Vehicle	Light Load (ft.)	Max. Load (ft.)	Partial Failure of One Subsystem	Brake Power Unit Failure
Alfa Romeo 2000 Berlina	144 (min)	146 (min)	316 ft.	170 ft. (min)
Oldsmobile Cutlass	240 (max)	208	639	433
Subaru 1400 Station Wagon	230	243	479	
Volvo 142E & 144E	161	185	271 (min)	226
Renault 12 Station Wagon	180	170	690 (max)	
Cadillac Fleetwood	200	201	585	516 (max)

Braking during a turning maneuver also showed two basic types of response (neglecting the case of a vehicle with a four-wheel antilock system). When either pair of wheels locked at the limit, the curved path of the vehicle quickly widened and cornering action ceased.

In an earlier HSRI study, four widely differing automobiles were tested in a program which led to the development of the testing procedures used in the work discussed above: a domestic station wagon, a domestic rear-engined compact sedan, a foreign luxury sedan, and a foreign luxury sports car. The straight-line braking test results from the study are summarized in Table A.2. The compromises inherent in station wagon design resulted in rear-wheel lockup when lightly loaded, but the Corvair's low performance ranking is more surprising.

Table A.2. Straight-Line Braking Performance on Wet and Dry Surfaces

Vehicle	Conditions	Maximum Deceleration Without Lockup (g's)	Pair of Wheels Locking First	Braking Efficiency*
Ford Station Wagon	Dry Concrete	0.75	Rear	0.74
Ford Station Wagon	Same + 450# Load	0.72	Front	0.71
Ford Station Wagon	Wet Painted Asphalt	0.33	Rear	0.72
Toyota 2000 GT	Dry Concrete	0.88	Front	0.86
Toyota 2000 GT	Wet Painted Asphalt	0.41	Front	0.89
Corvair	Dry Concrete	0.68	Rear	0.67
Corvair	Wet Painted Asphalt	0.31	Rear	0.67
Mercedes 250 Sedan	Dry Concrete	0.92	Front	0.90
Mercedes 250 Sedan	Wet Painted Asphalt	0.35	Front	0.76

*Defined as (maximum deceleration)/(coefficient of friction)

There has long been an interest in vehicle response to braking while cornering with regard to accident causation. In terms of vehicle control, a spin-out response is unstable and causes immediate loss of active control by the driver. A spin-out is caused when the rear tires lose the ability to produce side force, as occurs in rear-wheel lockup. When the front tires lock during a cornering and braking maneuver, these tires also lose the ability to generate side force, but a spin-out response does not occur. Rather, the yaw attitude of the vehicle remains confined within narrow limits. Under these circumstances, the path of the vehicle becomes a straight line and in this sense the driver no longer can control its motion. The driver can easily regain path control, however, by releasing the brake. The same is not true after a rear-wheel lockup has caused a spin-out.

Because of these vastly differing responses in terms of driver control, there has long been a debate as to the safety qualities of vehicles which exhibit either front wheel lockup first, or rear wheel lockup first. It has generally been presumed that the former is better and this has led to the wide use of braking systems with more braking power proportioned to the front wheels. The situation is not as clear-cut as it might appear at first glance, however.

If the weight of a vehicle is proportioned such that 60% is supported by the front wheels and 40% by the rear wheels, then it could be argued that the brake proportioning ought to be similar, i.e., 60% front and 40% rear. Under heavy braking, however, there is a substantial load transfer to the front wheels. Therefore, it has been argued that an even greater proportion of the braking power ought to be allocated to the front wheels. Systems with heavy front brake proportioning exhibit the best braking efficiency on dry surfaces—braking efficiency meaning the percent utilization of the available tire-road friction coefficient.

As the surface becomes more slippery, however, load transfer becomes less and a vehicle with heavy front brake proportioning will brake less efficiently. In fact, as the tire-road friction coefficient approaches zero, optimum brake proportioning approaches the front-to-rear static load distribution. From this discussion, it is clear that the subject of optimum brake proportioning is a controversial one.

With this background, a study by Lister [59] is of interest in illustrating the influences of brake proportioning and load transfer on braking efficiency. A summary of his study is shown in Table A.3. Note that the front-to-rear brake proportioning of each vehicle is greater than the front-to-rear weight distribution. Note further, however, that while dry road braking efficiency varies between 87% and 91%, wet road efficiencies range only between 70% and 76%. (For the Morris Six, for example, the dry road braking efficiency = .88(100)/1.0 = 88% while the wet road braking efficiency = .37(100)/.5 = 74%.) Thus, where circumstances would ordinarily dictate the best utilization of available friction forces—i.e., under wet conditions—braking effectiveness is actually reduced.

In another study of the variability of braking performance, AMF investigated six proposed antilock braking systems for their Experimental Safety Vehicle [60]. The different systems were evaluated by computer simulation for stopping distance in a straight line from 60 mph and for performance during a 0.3 g lateral acceleration turn, with fixed steer angle, from an initial speed of 40 mph. The surface skid number was also varied (either 20 or 80) as was the vehicle loading condition. The characteristics of the six systems are summarized in Table A.4. The simulation showed that systems 1, 4, and 5 were about equal, and better than system 3, in straight-line performance. System 1 (the most expensive) was the only one that did not show a significant increase in wet stopping distance when the optimum pedal force was exceeded.

For performance in a turn, the systems with anti-skid modulators exhibited no stability problems, and system 1 stopped shortest of all. The other systems (3, 4, and 5) could stop nearly

TABLE A.3

WEIGHT AND BRAKE EFFORT DISTRIBUTION FOR VARIOUS BRITISH CARS, AND THE EFFECT ON EMERGENCY BRAKING PERFORMANCE

	Car and Driver Only				Car, 4 People, and Luggage: Calculated Deceleration with Front Wheels Just Locking	
Automobile	Weight Distribution Front/Rear	Cold Brake Effort Distribution f/r	Weight Dist. (Calculated) at 1 g Deceleration	Value of μ (Calc.) Above Which Rear Wheels Lock First	$\mu=1.0$ Limiting Factor	$\mu=0.5$ Limiting Factor
1954 Morris Minor	55/45	62/38	82/18	0.40	0.88	0.35
Morris Six	56/44	68/32	81/19	0.47	0.87	0.37
Volkswagen	44/56	66/34	70/30	0.87	0.91	0.38
Mini Minor	61/39	75/25	85/15	0.62	0.84	0.35
Ford Zephyr	55/45	65/35	78/22	0.42	0.90	0.37
Singer Gazelle	54/46	68/32	76/24	0.61	0.90	0.37
Morris Traveller	52/48	65/35	77/23	0.56	0.91	0.37
Triumph Herald	53/47	74/26	73/27	1.10	0.88	0.36
Jaguar XK 150	47/53	64/36	63/37	1.10	0.91	0.39
Vauxhall VX 4/90	54/46	64/36	75/25	0.55	0.87	0.36
Vauxhall Velox	56/44	64/36	78/22	0.36	0.87	0.36
Ford Classic	52/48	64/36	72/28	0.58	0.88	0.37
Wolseley 6/110	57/43	37/63	70/30	0.00	0.90	0.38
Rover 90	56/44	63/37	77/23	0.35	0.90	0.38

Table A.4. Summary of Various Braking Systems Evaluated by AMF Simulation

System	Front Metering Valve	Front Proportioning Valve	Rear Proportioning Valve	Anti-Skid Modulator
1	None	None	None	4-wheel
2	Fixed	None	Fixed, Front-to-Rear	2-wheel, Rear
3	Fixed	None	Fixed, Front-to-Rear	None
4	Fixed	None	Variable, Front-to-Rear	None
5	Fixed	Variable, Right-to-Left	Variable, Front-to-Rear	None
6	Fixed	Variable, Right-to-Left	Variable, Front-to-Rear	2-wheel, Rear

as quickly if utilized optimally, but further pedal force increases caused lockup and spinning. The instability problem was least with system 5, greatest with system 3, in this subgroup.

The conclusion of the report was that, based solely on performance, system 1 (4-wheel anti-skid) was to be preferred, followed by system 6 and then 5.

A.1.2 Objective Evaluations of Vehicle Handling Performance. Vehicle braking performance is an area one might feel is most likely to be directly related to vehicle safety. It is also quite variable among new vehicles (as well as being sensitive to maintenance). Furthermore, the relationship between component design and final performance is reasonably well understood by automobile manufacturers, the performance dissimilarities presumably arising from differences in priorities and cost constraints.

The relationship between vehicle directional control properties and both highway safety and subsystem design are more of a mystery. Despite this mystery, or perhaps because of it, there exist more modern research reports on this topic.

This section covers investigations of the actual performance variations among either real automobiles or proposed designs.

A significant report by Okada, et al., of Toyo Kogyo Co., Ltd., has classified vehicle limit handling performance into five categories. The categories were based on parametric studies with a sophisticated digital simulation model [61]. The classifications have to do with the performance in turning maneuvers beyond the range of ordinary driving tasks, and may be identified both quantitatively and qualitatively. Figure A.1 plots each type of response as degrees of understeer (front wheel steer angle minus Ackerman angle) versus lateral acceleration. Of particular importance is the overlaying of all of the graphs at low lateral accelerations. This similarity points out the inadequacy of designing or evaluating cars for specific handling properties to be measured only at moderate lateral accelerations.

A qualitative description of each response type follows:

Gradual Drift: Vehicle understeer gradually increases with increasing lateral acceleration. Front slip angles are always greater than rear slip angles. The vehicle drifts at relatively low lateral accelerations despite considerable rear tire reserve grip. As the understeer becomes excessive, steering becomes difficult and responsiveness is very slow.

Sudden Drift: Vehicle understeer increases linearly to a certain lateral acceleration, then the vehicle suddenly drifts, exhibiting severe limit understeer. This might result from tires with high cornering stiffness but low maximum cornering force (i.e., certain radial-ply designs), or could be caused by nonlinear front roll stiffness.

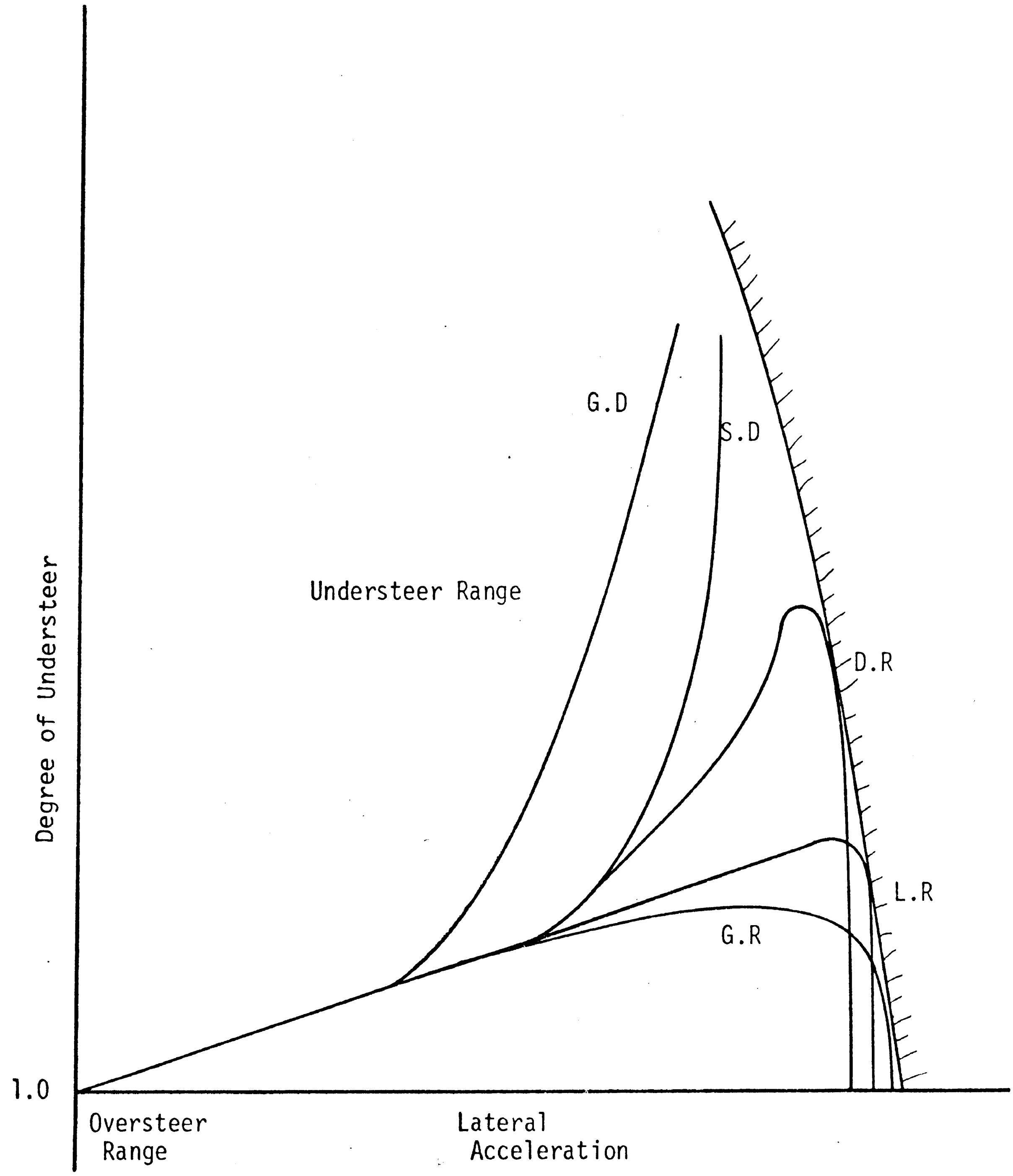


Figure A.1. Patterns of understeer characteristics.

Drift and Reverse: Understeer causes initial drifting, followed by a sudden switch to limit oversteer at still higher lateral accelerations. Again, this behavior may be due to tire properties or nonlinear roll stiffnesses. The first pair of tires to lose all grip are the rear ones.

Linear and Reverse: Understeer increases linearly with a sudden change to oversteer at the limit. This response type has the longest linear region and the highest limit, and is easiest to control at high lateral accelerations. However, there is little warning of the approach of the handling limit and the order of tire breakaway is unpredictable.

Gradual Reverse: Initial understeer gradually changes to oversteer as lateral acceleration increases. This might be caused by large rear roll stiffness or large tractive effects on rear tire cornering properties.

What was most significant about this research was the fact that, by altering roll stiffness characteristics, center-of-gravity height, or tire characteristics, the authors were able to cause the same basic vehicle to exhibit any and all of these responses in turn while demonstrating a constant degree of steady-state understeer at lower lateral accelerations! This is particularly interesting in the light of other parameter studies [60] which measured vehicle directional response in 0.4 or 0.5 g maneuvers and concluded that the handling was relatively insensitive to suspension variations.

In the U.S., the Experimental Safety Vehicle Program contained one of the first sets of comprehensive handling specifications. Although not directly based on safety research, the specifications encompassed the safety-related areas of rollover resistance, maximum cornering power, transient response times, controllability at breakaway, as well as tests of vehicle sensitivity to load variations, wet pavement, tire pressure changes, road bumps, and sidewind gusts.

As a result of the ESV effort in formulating these specifications, a number of analytical parameter studies were carried out by different ESV designers, particularly AMF, Volvo, and Alfa Romeo.

In the AMF study [60], it was found that actual performance could be controlled within limits by a balanced design of vehicle accident-avoidance subsystems such as springs, steering, engine and drivetrain, brakes, tires, etc. The performance envelope, however, is generally set by overall vehicle characteristics such as:

a) curb weight and location of center of gravity
b) load conditions
c) moments of inertia of the vehicle
d) overall dimensions of the vehicle, i.e., height, width, wheelbase, front and rear track widths, etc.

The Volvo research led to the final choice of suspension design parameters for the Volvo ESV [62]. As in the AMF study, it was found that reducing roll stiffness increased understeer. Understeer was reduced, however, by increasing the effective stiffness of the steering system. Other changes had relatively small effects, especially when contrasted with the severe changes in response that could be caused by load variations. An unexpected finding was that the sidewind sensitivity was markedly affected by changes in the static caster of the front wheels, and that settings which reduced path deviation (the ESV program's criteria for the standard) caused the vehicle to "feel" unstable. A final conclusion was that roll steer effects should be eliminated, as such effects can present serious directional control problems on older, heavily cambered roads.

In the Alfa Romeo study, both the ESV criteria and a closed-loop lane-change simulation were used to evaluate five "altered" vehicles [63]. The base vehicle was compared with an understeering configuration, a neutral steer version, and an oversteering configuration. Also tested was a vehicle with a twenty percent weight increase and a ten percent increase in radius of gyration; the purpose was to estimate the possible effects of future passive safety requirements.

ESV steady-state requirements were only met by the understeering vehicle, although the base and the over-weight vehicles were nearly acceptable. Only the oversteering car failed the transient yaw response requirement.

In the severe lane-change maneuver (the driver had to initiate a successful lane change when the distance to the lane blockage was half that required for a 0.4 g stop), the base and understeering vehicles were stable, while the other three lost control and ran off the road. Stability came at the expense of degraded handling quality, however, with a poor ratio of lateral acceleration to steer input angle. Although it failed ESV tests, the oversteering case exhibited good handling properties. The configuration with excessive weight, although clearly an understeering vehicle by ESV standards, had such poor response that it faired most poorly in the lane-change maneuver, showing the <u>least</u> stability.

The report was critical of the ESV approach to handling specifications, with its emphasis on smooth-track testing. "A fundamental characteristic of the vehicle, in order to judge its active safety quality, is its behavior on a rough surface. Such behavior involves not only considerations of comfort, but especially of roadholding."

Among the experimental work with actual vehicles is the test report by the Digitek Corporation which established the ESV criteria [64]. Six 1969 vehicles, ranging from a Jaguar "E" type, through domestic sedans and a station wagon, to a Lincoln Continental, were subjected to the proposed ESV testing procedures to determine the numerical values for the standards. The range of responses exhibited by the six cars was much wider than the range eventually allowed by the ESV specifications.

A plot of steering wheel angle versus lateral acceleration on the skid pad showed the Jaguar and the rear-heavy station wagon to have near-linear relationships up to their limits, indicative of neutral-steer characteristics. The larger domestic sedans required ever-increasing steer inputs to maintain higher cornering speeds, with severe understeer at their somewhat lower limits. The Rambler compact tested had such slow steering response that it required over twice the steer input of the Jaguar for mild cornering and about four times as much input, amounting to virtually a complete rotation of the steering wheel, to corner at one-half g!

The cars were tested for their maximum cornering power on wet and dry skid pads for a variety of tire pressures. The results were quite dependent on front tire pressures. The dry-road range was spanned by the Lincoln and Rambler (0.55 to 0.58 g's, and 0.54 to 0.62, respectively) at one end and the Jaguar (0.70 to 0.77 g's) at the other. The control-at-breakaway and cross-wind sensitivity tests also showed ranges of a factor of two between the best and worst performing vehicles.

A British investigation by Jacobson [65] examined the safety and handling aspects of punctured tires, and did considerable research on the effect of off-design tire pressures on directional control performance. He claimed that five to eight percent of all British cars have significantly mismatched or incorrect tire pressures and suggested that a serious safety problem may be caused by slow deflations which go unnoticed until a sudden turning or braking maneuver elicits an exaggerated or unpredictable response.

The author tested numerous vehicles and many combinations of wheels and tires, under many load and road conditions. Part of the program involved the lowering of inflation pressures in increments to determine the thresholds of controllability for the average driver. On a good skid pad, with properly inflated tires, the test vehicles achieved from 0.56 to 0.96 g's lateral acceleration, depending on the car, before control was lost. With pressures of from ten to fifteen psi, typically only 0.25-0.30 g's could be attained before the tire would leave the rim or its sidewall would contact the road surface.

A final set of experimental studies of the handling differences between automobiles were performed at HSRI. The first was the previously mentioned four-car study: the Ford station wagon, Corvair, Mercedes 250, and Toyota 2000 GT [44]. Besides the braking tests already reported on, the cars were subjected to a variety of handling tests.

In a test of the response to rapid steer inputs, recorded as lateral acceleration versus final steer angle, the Toyota and Corvair showed rapid and linear responses with suddenly-approached limits. The Ford reached its limit more gradually, but the response was slower (i.e., greater steer inputs were always needed to reach a given cornering radius than for the other cars); the Mercedes fell in between. When these maneuvers were plotted as peak yaw rate versus peak lateral acceleration, the Corvair alone showed a trend toward rapidly increasing peak yaw rates as the severity of the maneuver increased. This was evidence of the Corvair's tendency to spin out at its limit. Of additional interest was the fact that runs were also made with off-design tire pressures—this had little effect on the Corvair and Mercedes graphs while leading to much more scatter near the limit for the Ford station wagon and Toyota sports car.

A test of roadholding on a rough surface measured the decrement in cornering performance as speed increased, and ranked the cars in order of Mercedes (best), Corvair, Ford, and Toyota. The results were found to be very dependent on tire pressures. Also dependent on inflation pressure, as well as on load condition, were the performances in the sinusoidal steer test. High speed or off-design pressures caused divergent results for the Corvair at even moderate steer angles, and for the Toyota as the test became more severe. The final test was an attempt to induce vehicle rollover and again the responses were all different. Only the Corvair rolled, and again the response was made significantly more severe when inflation pressures were incorrect.

Two years later, HSRI tested a sample of eight different 1971 production cars for their handling sensitivity to serious degradation of their steering and suspension systems [45]. Although component degradation is not directly relevant at present, several comments in the summary report are of interest. First, "....the range of limit handling performance exhibited among new cars, as derives from design differences, is much larger than the in-use changes in performance of individual vehicles deriving from degradation of steering and suspension system components." The authors further noted that many degraded conditions which had relatively insignificant effects on limit performance involve factors which increase the demand of lower-level driving tasks. The increased level of driver attention required by such conditions could easily lead to early driver fatigue, and that this might in fact constitute a larger safety problem than the slight deterioration in limit performance properties.

In the most recent HSRI report, Ervin [66] noted that many vehicles tested in the earlier programs [43,44] had shown a pronounced response asymmetry, performing differently in sine-wave steer input tasks when the initial steer was to the right than when it was to the left. Also, it was pointed out that some cars were so sensitive to side-winds that they might pass test criteria under some wind conditions and spin out under others. It was also noted that particular combinations of brake and steer applications could cause some vehicles to overturn on smooth surfaces.

A.2.3 Subjective Reports on Safety and Handling. There are many articles which postulate possible relationships between vehicle design, performance, and safety. These are of interest because they point out hypotheses which researchers may wish to try to prove or disprove as sufficient data and methodologies become available.

Janeway [67] has prepared a good summary of the ideal objectives in creating a good-handling vehicle, and of the relations between design and handling performance. The report is a review of the factors in vehicle design which determine handling properties and of the (1962) state of the art knowledge of the ties between safety and handling. The areas are thereby identified where improvements might reasonably be made. The aspects concerning the author are two in number: (1) the inherent directional stability under road and wind inputs, and (2) the ease and precision with which vehicle velocity (direction and/or magnitude) may be set or altered at the driver's will. Even an ideal design, of course, must work within the finite limits imposed by tire-pavement friction, and therefore remains at the mercy of variations in road and weather conditions for which only driver judgment can compensate.

For cornering stability, sufficient understeer is best assured by placing over fifty percent of the weight on the front wheels, even at maximum vehicle load. A high track/rear-roll-center-height ratio will minimize rear lateral weight transfer (an oversteer effect). A high ratio of track width to center-of-gravity-height will lessen the rollover tendency. Rear-engined cars often fail in all of these criteria, because they are usually small (which also means that a neutral or rearward-biased weight distribution is proportionately more affected by extra passengers than in a larger car), often narrow, and always have independent rear suspensions (which contributes to oversteer through rear roll camber effects and high roll centers). Station wagons also tend toward rear weight bias, and have poorly defined maximum allowable loads.

Methods exist for introducing rear understeer effects. Differential tire pressures are often used, but are not preferable because of the reliance upon the driver for proper maintenance. Rear suspension steer effects can be used, but compliance steer is to be preferred over the more common roll steer approach; roll steer effects exhibit a time lag in transient maneuvers as well as introducing objectionable dynamics if excited at certain frequencies.

Aerodynamic stability can also be obtained only with an understeering car, according to Janeway. Streamlining moves the center of side-wind pressure forward, necessitating a further forward placement of the center of gravity. (The author does not foresee a return of fins, helpful though they may be!) Small cars are again at a disadvantage, due to high surface-to-weight ratios.

Dynamic handling improvements are dependent on adequate suspension control (shock absorber damping), fast steering ratios, minimized roll-steer effects, and understeer at all expected speeds and lateral accelerations.

A later NHTSA report also deals with the needs of vehicle performance [68]. Agreeing with Janeway on the handling problems, especially on the role of gusty side-winds in the degradation of safe vehicle operation, the report also lists as accident avoidance factors, "vehicle stopping capability, tire limitations, headlight limitations [and] acceleration...capability." Two interesting points concerning vehicle safe-handling problems were made. First, "design of front-end suspension systems is a compromise between the need to keep the tires in contact with the road under all conditions while providing a comfortable ride and minimum degradation in steering capability." Secondly, it is observed that the minimum speed at which hydroplaning can occur on wet surfaces is a function of tire inflation pressure.

An article by G. Jones indicates the greater emphasis placed on active safety and the role of the vehicle by foreign manufacturers [69]. Speaking as a member of the British Leyland ESV project, he said that "....from a broad consideration of all the available information and from our own accident investigations, it is evident that avoidance of accidents is no less a priority than occupant protection and that the handling and stability of vehicles is a subject of great importance....[The] designer has to consider.... side-wind stability, traction under poor grip conditions, stability under braking and vehicle ride."

Noting the lack of relevant data, Jones says that "it would be of great benefit to have clear objective evidence of required performance levels based on accident investigations but inevitably the interaction of a number of factors involved in each individual accident makes it difficult to establish this. Investigations are, however, being carried out to try and relate accidents to handling characteristics. Experience of vehicles having either oversteered or understeered prior to accidents has been sufficient to emphasize the basic importance of these effects relative to safety."

The importance of understeer-oversteer measures is indicated in a comparison of lane-change maneuvers performed by an understeering vehicle and by the same vehicle in an oversteering configuration due to drastic tire pressure changes. The understeering car completed the maneuver successfully. The oversteering vehicle, because of its slower response, developed a large phase lag between steer input and motion output, contrary to driver expectations. In a limit-type maneuver, the vehicle continued turning across additional lanes after the steering wheel had reached full reverse lock.

The author concludes that driver control is maximized when understeer is present and when the yaw natural frequency is high and phase lag is at a minimum. To accomplish this, one would like to combine stiff tires (high cornering coefficient), long wheelbase, and low yaw inertia. Conflicts arise, however; safety regulations force inertias up, while long wheelbases slow the steer ratios and increase turning circles, thereby reducing maneuverability. One answer, then, is to use the widest, stiffest tires compatible with the vehicle.

The entire question of what comprises "safe handling" is viewed rather uniquely in a report by Bergman of Ford Motor Company [70]. He departs from the approach that vehicle performance limits must be increased. Testing twelve random vehicles revealed mean capabilities of 0.83 g's lateral acceleration and 0.75 g's longitudinal deceleration; research had shown that only a small fraction of actual drivers ever attempt cornering at even 0.35 g's or braking at 0.60 g's. Table A.4 reveals the minimum safety margin that is not utilized by the driver.

Table A.4. Minimum Safety Margins—Vehicle Capability Versus Maximum Demands

Mode	Maximum Demand	Capability	Dry Road Safety Margin	Wet Road (μ=.4)
Cornering	0.35 g's	0.83 g's	59%	12%
Braking	0.60 g's	0.75 g's	20%	-50%

The author's argument is that driver limitations and the driving situation dominate the safety picture, modified by vehicle and environmental conditions. With the exception of severe braking on wet roads, the vehicle's limits of capability are too high already for modifications of those limits to affect highway safety.

It is pointed out that the cornering limit of the average vehicle is actually higher than its braking limit, yet a much smaller percentage of the limit is utilized by normal drivers. This is presumably due to the relative <u>ease</u> with which a driver can perform each maneuver: steer maneuvers require enough effort, coordination, timing, and proper recovery that the driver finds it far simpler to decide upon a braking response to emergencies. This is the basis of the author's hypothesis that the ease of control, as estimated by average drivers, is a far better measure of a vehicle's safe performance than the objective open-loop or skid pad tests usually suggested. The aim of designers would then be to create automobiles which encouraged their drivers to use the built-in capabilities when confronted with a potential accident.

In other work, Segel [71] has also attempted to define the handling "problem" in terms of safety. He proposes four questions to evaluate handling subjectively: (1) Does the vehicle respond to steering so that one may change course rapidly, precisely, and easily? (2) Does it follow a selected path irrespective of aerodynamic or road disturbances? (3) Do the tires remain in contact with the road irrespective of ride disturbances? (4) Does the vehicle respond to steering displacement and force levels in a manner conducive to safe control in emergencies?

In the discussion following the article, the author states that he suspects all American automobiles have similar steady-state or fixed control dynamic characteristics, and that he doubts that accident rates can be related to such steady-state measures of performance as understeer or static margin. Rather, the "handling" differences arise out of different steering system characteristics, including required force levels, road feel transmitted, gear ratio, etc. Segel's concern with subjective measures of controllability parallel to some degree those of Bergman in the article above.

In a general indictment, McCaffrey [72] claims that North American cars have, "in the last twenty-five years [exhibited] serious deterioration in their high-speed handling qualities," primarily due to the emphasis on ride quality and extreme understeer. Sudden steer or wind inputs create objectionable oscillatory roll and/or yaw motion. He calls for less yaw inertia and more yaw damping.

As a final comment on performance and safety, Orme, et al. [73] note that vehicles with lower wind resistance require less tractive force for the maintenance of high forward velocities, and therefore offer a greater margin of safety for sudden maneuvering or for resisting disturbances. Although it is possible to imagine situations in which this could be significant, it is not mentioned as a possible important accident causative factor.

A.3 The Vehicle/Driver Interface

In the system composed of the driver, vehicle, and roadway, the number of variables potentially influencing driver behavior is oppressively large. Man is an adaptive element in this system, but with finite adaptation limits. Within the limits of his capabilities man is able to adapt his performance in such a way as to produce an invariant system response over a wide range of system parameters. This property is called the "U-Hypothesis" [74] and is illustrated in Figure A.2. For example, the friction load on a control knob can

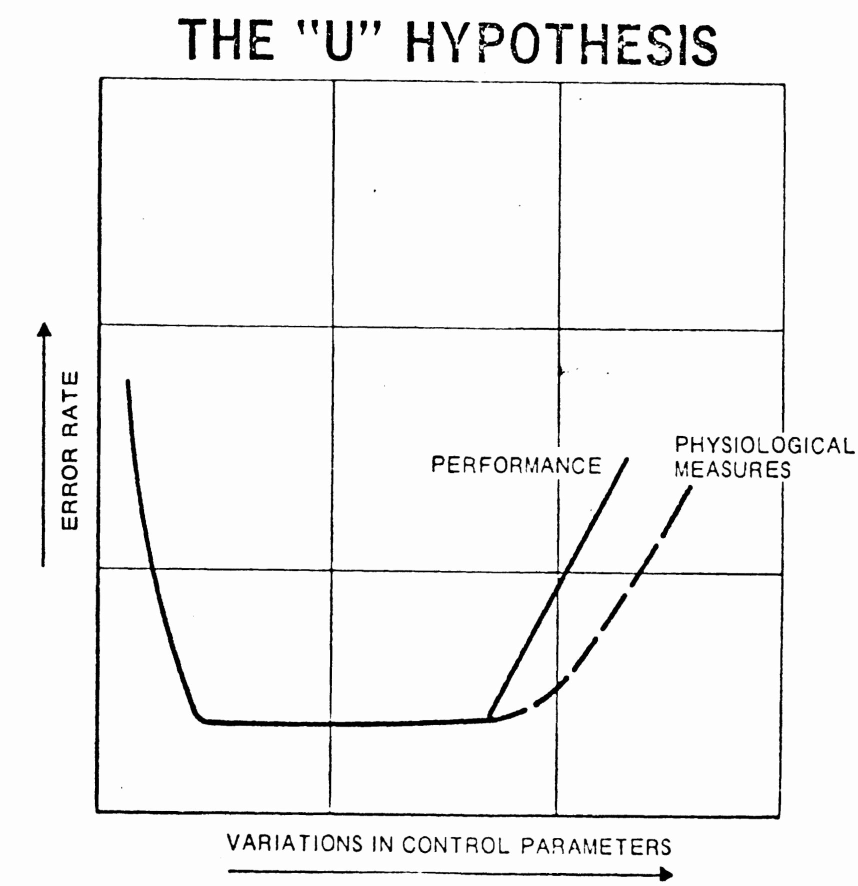


Figure A.2

be varied over a wide range with no change in the ability of man to move the knob. However, when performance does deteriorate, it usually decreases sharply at extreme values and the error accumulates rapidly, and, in the case of automobile driving, sometimes fatally. In the words of Sullivan and Meister [75] "...man is sufficiently flexible that he can adapt to some of the most flagrant abuses of his abilities and capacities without the least measurable decrement in performance. It is only when a precipitating stress factor is introduced or the limits of his adaptive tolerances are surpassed does his performance degrade significantly." Man's adaptability in driving is precisely the reason it is so difficult to separate purely vehicle-related causation factors from the accident record.

The two major areas of driver/vehicle interaction are in (1) the ergonomic matching of the vehicle interior (e.g., seat positioning, location of steering and braking controls, required control forces, etc.) to the driver's physical dimensions and strength capabilities and (2) the driver's performance in the vehicle steering control loop. These areas are not completely separated, of course, since the former influences the latter. Nevertheless, most research has treated these areas as mutually exclusive.

A.3.1 The Driver Working Environment. In designing the driver's work space, consideration must be given to the stimuli used by the driver, and to the speed, precision and muscular force capabilities which the driver can call upon.

The most important stimuli are visual [76]. Also important are kinesthetic (feel, touch, tension in muscles), static (equilibrium-semicircular canals), auditory (ears), and in some emergency situations, olfactory (nose). A constant stimulus is ignored by the brain so that a stimulus, to be readily sensed, must be intermittent.

The eyes of a driver may have certain defects, e.g., myopia, astigmatism, cataracts, etc. The eye requires time to adjust to a level of illumination. Large variations in illumination are dangerous. The presence of large numbers of red lights, e.g., tail lights, stop lights, parking lights, advertising, traffic lights, road repairs, etc., can form a constant stimulus which is ignored by the brain. Further, variation in the intensity of tail lights can cause errors in judgment. A dull light appears to be further away than a bright light.

According to Platt [77], the brain can analyze about one stimulus per second. Thus, in some measure, the driver acts as a sampled data system controller.

The brain responds more quickly to an audio stimulus (i.e., tire squeal) than to a visual one. If practical, then, it is desirable to supplement a visual stimulus with an audio one. An example might be a radio signal transmitted from a traffic sign and received in the car.

Considerations in matching the interior of a vehicle to driver needs include seating, the possibility of the foot becoming trapped between the top of the accelerator and the bottom of the brake pedal, the inclination of the accelerator pedal, clearance under the steering wheel for knees, the steering wheel diameter, etc. [78]. Some twenty-one body dimensions are considered to be important with respect to this matching:

General

1) Height
2) Weight

Body Heights

3) Sitting height, erect
4) Sitting height, normal
5) Sitting eye height, normal
6) Shoulder height - seated
7) Elbow height - seated
8) Knee height - seated
9) Popliteal height - seated (knee at 90° and 135°)
10) Thigh height - seated (at popliteal, trunk and midpoint region)

Body Breadths

11) Shoulder breadth
12) Elbow breadth
13) Seat breadth
14) Shoe breadth

Body Depths

15) Chest depth
16) Abdomen depth (relaxed) - seated

Body Lengths

17) Buttock-knee length
18) Buttock-popliteal length
19) Shoe length

Dynamic Body Measurements

20) Functional arm reaches
21) Functional leg reaches

With respect to seating, the following dimensions were recommended:

1. Seat Breadth (measured horizontally on seat surface). 18 in. for a single seat; 20 in. per person on multiple seat.

2. Seat Depth (measured on seat surface from the SRP* to a vertical plane tangent to the most forward point on the front of the seat). Optimum 18 in.

3. Seat Height (measured vertically from the floor to a horizontal plane tangent to the highest point on the cushion). Maximum 14 in., minimum depending on location of foot pedals and field of vision.

4. Backrest Breadth (measured horizontally at elbow height). 20 in. per person.

5. Backrest Height (measured from the SRP* to a horizontal plane tangent to the top of the backrest). 17 in. to 21 in.; not critical if in this range.

6. Inclination of Seat Surface (measured from the horizontal). 7°, but adjustable through a wider range.

7. Inclination of Backrest (measured from the vertical). 22°, but adjustable through a wider range.

8. Range of Fore-and-Aft Adjustability. A minimum of 8 in., in increments of 1 in. or less.

9. Range of Vertical Adjustability. A minimum of 5 in. in increments of 1 in. or less.

10. Armrest Height (measured vertically from seat surface). 9 1/2 in.; preferably adjustable from 8 in. to 11 in.

*The SRP, or Seat Reference Point, lies at the intersection of the plane of the undeflected seat surface with the plane of the backrest in line with the center of the steering column.

11. Seat to Roof Distance (measured vertically from SRP to roof). A minimum of 38 in. with seat in lowest position.

12. Steering Wheel-Seat Distance (measured vertically from lowest point on wheel to nearest point on seat surface). Minimum 5 1/2 in.

13. Backrest-Dashboard Distance (measured horizontally, at knee height, from backrest to dashboard or closest structure). Minimum 26 in. with seat rearmost, minimum 22 in. with seat foremost.

In the area of control locations, McFarland, et al. [79], indicate that ...."hand controls should be between the shoulder and waist levels, and in front of the operator, for the greatest speed and accuracy of movement." For continuously-operated controls, placement at about elbow height is best. Foot controls should be not more than 10 inches above the floor with 8 inches the optimum. The axis of a rotating foot pedal should be about 4 inches from the heel for maximum force. For minimum strain, the thigh should be horizontal and the lower leg at 45° from the vertical. If the thigh is elevated from the seat, a greater force can be exerted. To accommodate persons of different body size, there should be 8 1/2 inches of adjustment in the pedal rod and foot rests. The maximum speed of body motion in operating controls cannot be expected to exceed 10 ft/sec, for short movements of less than two feet, if accuracy in stopping is required. If speed is stressed, speeds may exceed 20 ft/sec.

Resistance to movement gives the operator a control cue. Accuracy of movement increases after a small initial force has been applied, and optimum ranges seem to be 5-30 pounds for hand controls, and 7-60 pounds for foot controls.

Within the passenger compartment, the ideal temperature range is 68°F to 72°F. Manual dexterity falls off markedly below

50°F. Relative humidity is preferable in the range between 25 and 50 percent. High humidity is permissible for temperatures up to about 90°F, but humidities below 15% cause discomfort to the eyes and nose. In general, 35 to 40 cu.ft./min. of fresh air should be supplied for each person. The noise level should not exceed 75 decibels if damage to hearing is to be avoided. At 55 decibels, conversation is intelligible at several feet; at 65 decibels, communication is difficult; at 75 decibels, communication is marginal. Reducing the exhaust gas velocity to below 500 ft/sec with only a small pressure variation will render the gas flow relatively quiet. Vibrations of frequencies between 25 and 40 cycles per second, and 60 and 90 cycles adversely influence binocular vision. The undesirability of vibration increases with amplitude and frequency.

A.3.2 The Human Operator in the Driving Task. The driving task can be broken down into three functions: navigation, guidance, and control [80]. Navigation includes those functions which relate to the task of selecting a safe speed and planning a long-term path on the roadway in view ahead. Control activities include the physical manipulation of the vehicle. While performance at the control level is overt, that at the guidance level is a decision process. The driver must evaluate the immediate situation, make appropriate speed and path decisions, and translate these into control actions. In controlling the vehicle, the driver exercises lateral and longitudinal control through the steering wheel, accelerator, and brake. The control actions of the driver represent the primary area of direct interaction of the driver and vehicle.

Since the early 1950's, many studies have been carried out in attempting to understand and describe the driving process in mathematical terms. Early attempts were generally based on relating human tracking task performance to the driving task [81]. Such tracking tasks can be classified according to the nature of the input to the human controller [82].

1. In a COMPENSATORY system, the controller's task is to null an error signal to zero. The absolute output of the system is of no consequence.

2. In a PURSUIT system, the controller's task again is to null the error to zero, but unlike a compensatory system, both the system output and the input to the system are displayed to the driver. Thus, the human controller may distinguish individual properties of these signals by direct observation, rather than just a difference as represented by an error signal.

3. In a PREVIEW system, the displayed information is similar to that of a pursuit display except that input information extends from the present time until some time in the future. Preview control is more akin to the driving task and can be likened to a curving road being displayed in front of the driver.

These basic definitions of tracking task functions have led to numerous studies of operator performance under controlled experimental conditions [83-87]. The result of these studies has been the development of a linear transfer function for the continuous performance of the human operator which takes the form [88]:

$$Y(s) = \frac{K e^{-T_D s}(1 + \tau_L)}{(1 + \tau_N s)(1 + \tau_I s)}$$

where K is a gain which is adjustable by the operator over a range of 1 to 100; T_D is a reaction time (or transport) delay; τ_N is a coefficient of first-order lag inherent in the neuromuscular system; and τ_L and τ_I are, respectively, lead and lag coefficients which can be adjusted by the human along with K so that the output performance corresponds to some preset performance criteria.

Human operator performance is not linear and not continuous, however, and numerous attempts have been made to account for observations of nonlinear and intermittant performance. Bekey [89] proposed a simple model of the human operator consisting of a periodic sampler, a first-order hold and a time delay plus first-order lag term. His model best matched experimental data with a sampling period of 0.33 sec. and a delay time of 0.06 sec. Others who have developed intermittant, nonlinear models of the human operator include the Lemay-Westcott "Force Program" model [90], the Young sampled data model for eye tracking [91], the Elkind combined force program and sampled data model [92], the Costello Surge model [93], and several more [94-96].

Unlike a simple tracking task, the full visual field is available, so a driver has many cues to assimilate. This diversity of information makes the definition of cues used by the driver very difficult. Regardless of this difficulty, however, the general closed-loop character of driver steering control is shown on Figure A.3 [75]. The controlled element consists of the lateral/directional dynamics of the vehicle and the steering system, as well as the geometry of the visual field from which the driver extracts the guidance and control cues. The roadway environment provides inputs to the system, including path commands to be followed and disturbances (e.g., bumps) to be regulated.

The cues which the driver may use to carry out guidance and control functions are listed in Table A.3. The vehicle motions involved are depicted in Figure A.4 [97]. In Table A.3, the portion of the field of view which probably dominates sensation is shown as the "estimated source." The form of the cue or "estimated basis" is given in the next column, and the driver is assumed to be responding as if he were operating on the motion variable shown in the first column.

SIMPLIFIED REPRESENTATION OF THE DRIVER-VEHICLE-ROAD SYSTEM

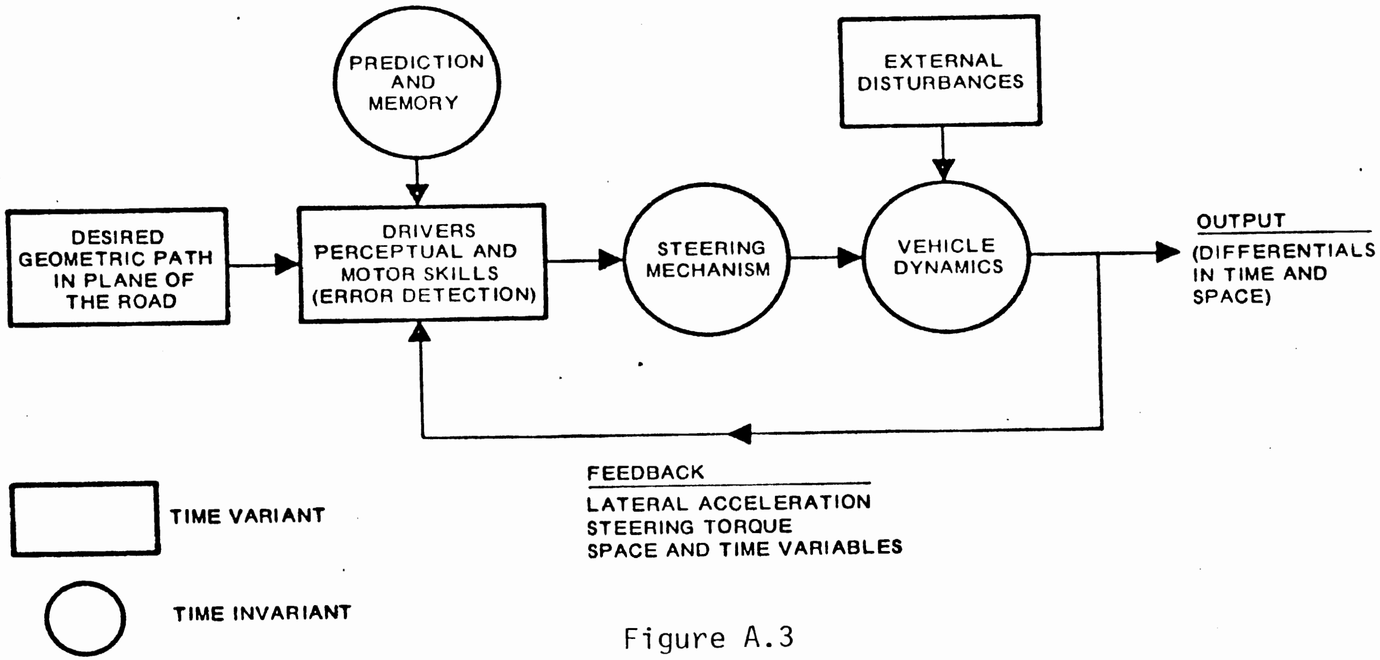


Figure A.3

Table A.3. Possibilities for Visual Sensation

Motion	Estimated Source	Estimated Basis
Heading Angle, ψ	Central field	Angle between a reference line on the vehicle and a reference line in the roadway.
Heading Rate, r	Entire field	Angular motion of the entire visual field.
Path Angle, γ	Near, peripheral field	Streamer-like motion of textural points, or a visual pattern.
Path Angle Rate, $\dot{\gamma}$	Near, peripheral field	Rate of change of streamer-like motion of textural points.
	Central and far fields	Curvature of the path, which provides for feed-forward, pursuit-like control operating on the visual pattern.
Time-Advanced Lateral Deviation $y_1(t+T)$	Central and far fields	Displacement at a preview distance.

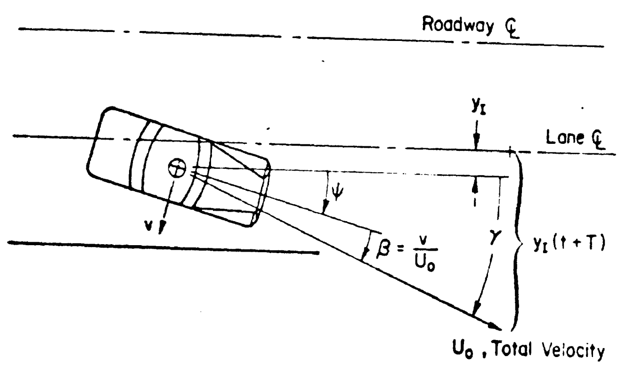


Figure A.4. Directional Motions of a Car.

The motion variables in Table A.3 may be sensed visually or may be "computed" from visual sensations. Heading angle arises directly from the visual field geometry. Path angle and path angular rate may derive from streamers of moving reference points [98-101], or rates of change of these streamers. Vehicle motions are probably "computed" by the driver which results in a pattern which he can compare with an external pattern. The comparison then produces a stimulus to which the driver responds. An example is given by a curved road which produces a path angular rate input to the driver with a resulting steering response.

While the elements of the steady-state driving task have become reasonably well understood in recent years, the field still remains an artistic, empirical science. For transient and emergency driving maneuvers, the understanding is much less developed. Further, the influences of different matches of driver and vehicle characteristics are just now being examined. Recent work at the Texas Transportation Institute [102] was carried out to evaluate the performance of four widely differing vehicles with eight different drivers. The drivers were asked to drive their vehicles through ten different handling tests ranging from "replicative" maneuvers such as braking in a turn, roadholding in a turn, drastic steer and brake, etc. [35], to "surprise" maneuvers such as a sudden obstacle, blind corner, sudden lane change, etc. The performance parameters which indicated the largest differences between vehicles (presuming driving performance was uniform) included sideslip angle, yaw rate, initial steer angle, and sideslip angular rate. The parameters which indicated the least differences between vehicles were roll angle and longitudinal acceleration. In general, the maneuvers which most frequently produced differences in driver-vehicle performance were transient maneuvers such as a lane change or avoidance maneuvers. When a loss of control (spin-out) occurred on a low-friction surface, it always occurred during the recovery phase of an avoidance or lane-change maneuver. As driver response requirements increased in the tests, performance also increased up to a point and then fell off. This behavior suggests that drivers tend to "give up" if the task becomes too difficult.

Presently, there are at least four programs underway which involve the development of simulators to further study driver-vehicle handling performance [103-106]. Potentially, these efforts will add further to an understanding of the role of vehicle handling in accident causation. Nonetheless, a definitive understanding of the many factors that influence driver and vehicle interactions is still many years distant.

A.4 The Vehicle/Roadway Interface

Interaction between the vehicle and the roadway is through the forces generated at the tire-road interface. These forces can be separated into three categories:

a. Friction Forces

b. Geometric Forces

c. Surface Irregularity Forces

The influence of each of these as a potential accident causal factor is discussed in the following subsections.

A.4.1 Friction Forces. The friction forces between the tire and the road are influenced by the tire, the road surface texture, and surface contaminants such as water, oil, ice, or snow.

The properties of the tire which are important include tread pattern, tread wear, tire construction, and rubber compound. Tread pattern has the most influence when water is on the pavement surface. A pattern that allows the surface water to be squeezed out to the sides of the tire-road contact patch will provide the best wet surface traction [107]. On a dry surface, however, tread pattern has much less influence [108]. In fact, a bald tire has slightly better tractive characteristics on a dry surface than does a tire with a grooved tread pattern.

Tread wear is important in wet traction. Several studies have shown that under wet surface conditions tire traction decreases with tread depth [107, 109-113]. Under dry pavement conditions, however, certain kinds of tread wear patterns such as severe shoulder wear have been shown to actually increase maximum cornering force levels [35].

With the recent advent of the wide use of radial tires, there has been much interest in the influences of tire construction on vehicle handling and traction. Radial tires, appearing to be partially flat, give the impression of having less cornering force capability. Nothing could be further from the truth, however. The most outstanding advantage that radial-ply tires have over conventional bias-ply tires is a relatively uniform and constant ground pressure over the contact patch. In contrast, the ground pressure in the contact patch for a bias-ply tire varies greatly from point to point, as tread elements pass through the contact patch and undergo a complex localized squirming motion. The belt in a radial-ply tire is sufficiently flat and laterally rigid to greatly reduce these motions and distortions, with a resulting minimization of scuffing and wear. In cornering maneuvers, a radial tire requires a slip angle of perhaps only 2° to produce the same side force as an equivalent bias-ply tire with a 3° slip angle.

The role of the rubber compound in producing friction forces is complicated and remains somewhat controversial. Most agree that friction between the tire and road surface is made up of adhesion and hysteresis components. Adhesion friction arises from the tire-road interface shear stress in the tire and is of primary importance under dry surface conditions [114]. Hysteresis friction is caused by damping losses within the rubber when the latter is "flowing" over and around the road surface asperities. Hysteresis friction is of most importance under wet surface conditions. A good discussion of the tire-road friction mechanism can be found in References 108, 114, and 115.

The influence of road surface properties on tire-road traction can be illustrated by the surface classifcations proposed by Allbert and Walker [116] and then later modified by Kummer [114]. As shown on Figure A.5, pavements can be classified according to two different asperity size scales which affect friction and contact patch water expulsion properties:

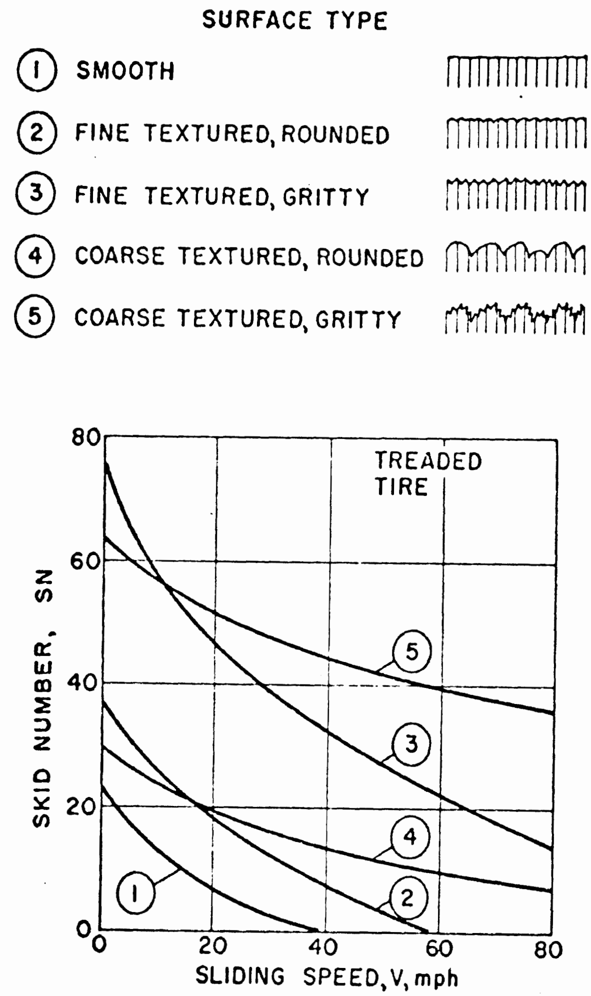


Figure A.5. Classification of Pavement Surfaces According to Their Friction and Drainage Properties.

1. Smooth surfaces (bleeding asphalt, highly polished stone asphalt or cement concrete surfaces).

2. Fine-textured, rounded surfaces (worn stone or silica sand surfaces of fine gradation).

3. Fine-textured, gritty surfaces (new silica sand or metal carbide-epoxy surfaces).

4. Coarse-textured, rounded surfaces (polished slag or limestone surfaces of large gradation or uncrushed gravel surfaces).

5. Coarse-textured, gritty surfaces (new slag pavements consisting of large particles, possessing large- and small-scale macroscopic roughness, or limestone surfaces which contain more than 10 percent sand-sized siliccous material).

The gritty or harsh microtexture of a surface determines its basic friction properties and hence its low-speed skid number. The coarse or open macrotexture of a surface determines its contact patch water expulsion characteristics. Water expulsion characteristics, in turn, determine the variation in skid number with speed.

A.4.2 Geometric Forces. The role of geometric forces in the tire-road interface is straightforward in some ways, but somewhat circumspect in others. The geometric forces that arise from curvature, grade, and superelevation are well understood and need no further discussion here. There is a secondary role that roadway geometrics influence, however, that is not widely known. It has been shown [117] that pavement width and cross-slope have an important bearing on the accumulated water depth on road surfaces under rainy conditions. Further, it is well documented that surface water depth has a large influence on pavement skid resistance [107, 109]. Finally, it has been demonstrated that sections of road having moderate cross-slopes and wide widths of paving (e.g., a wide gradual curve of radius one mile with a paved, superelevated outside shoulder) can be very dangerous during wet weather [118]. While it can be demonstrated that such curves can be easily negotiated under steady cornering conditions, a situation calling for an emergency handling maneuver can be disastrous. Thus, roadway geometrics contribute to a reduction in available skid resistance by causing increased water accumulations on the road surface and a lower margin of safety for emergency situations.

A.4.3 Surface Irregularity Forces. Several researchers have attempted to relate roadway roughness to various aspects of vehicle handling performance. (It should be noted that the purpose of almost all early studies of roadway roughness was to ensure vehicle ride comfort. In general, there is a direct tradeoff in vehicle suspension design with regard to providing ride comfort versus roadholding ability. Only recently, it seems, has roadholding ability been of much concern to the U.S. automobile manufacturer.) The earliest published material on vehicle responses to road roughness is apparently that of Quinn [119]. He modeled the vehicle suspension system in terms of a transfer function using techniques already well developed in the aeronautical field. This work and much of his subsequent work [120, 121] was primarily ride-related. In fact, the emphasis on ride factors as influenced by road roughness has led the ISO to develop a proposed standard for generalized road inputs [122, 123].

Although many theoretical attempts have been made to optimize vehicle suspension systems for combined ride and roadholding properties, the earliest apparent experiment work (i.e., work available outside the automotive industry) on factors other than ride is that of Brickman, et al. [124]. Their concern was with the influence of road roughness on braking efficiency. Although the work showed a definite relationship between road roughness, surface friction, and braking performance, the results are not easily extended to actual practice. The work was carried out on a laboratory test apparatus with the test tire mounted on a rigid axle. The random "roadway" was produced by an undulating rigid surface under the tire. No suspension components were included.

Quinn's most recent work has been concerned with the effects of road roughness on vehicle steering [125]. In this work he investigated the influence of road roughness on vehicle cornering maneuvers. He concluded that roughness alone could precipitate a spin-out in a passing maneuver if a driver had to react quickly in returning to his lane. The work is open to serious question, however, due to the many assumptions used in deriving the results. For example, the vehicle was modeled as a sort of bicycle without a roll degree of freedom and without a suspension system. Further, the lateral tire forces were assumed to build up instantaneously with slip angle and were not assumed to be influenced by transient effects. While the work is perhaps useful as a first step, it can by no means be considered definitive.

A more realistic approach to investigating roadholding in the presence of surface undulations has been initiated by Schaippati [126]. While recognizing the complexities of the problem, he has begun a study which includes the driver response as well as that of the vehicle to road irregularities. The work is far from complete, however. Preliminary studies have shown that artificially constructed surfaces can be used to simulate actual bumpy surfaces and that the response of the vehicle/driver system is similar in both cases.