NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT **184**

INFLUENCE OF COMBINED HIGHWAY GRADE AND HORIZONTAL ALIGNMENT ON SKIDDING

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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INFLUENCE OF COMBINED HIGHWAY GRADE AND HORIZONTAL ALIGNMENT ON SKIDDING

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AREAS OF INTEREST:

- HIGHWAY DESIGN
- PAVEMENT PERFORMANCE
- HIGHWAY SAFETY

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1978

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Transportation Research Board.

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FOREWORD

By Staff
Transportation Research Board

Implementation of the findings from the research described in this report will be helpful in reducing wet-weather skidding accidents on many Interstate and freeway long-radius curves. The AASHTO geometric design procedures—as described in *A Policy on Geometric Design of Rural Highways, 1965* and *A Policy on Design of Urban Highways and Arterial Streets, 1973*—provide for realistic design of highway curves. However, misinterpretation of the procedures has resulted in the design and construction of long-radius curves on multilane highways with inadequate superelevation for surface drainage. In some cases this contributes to an extraordinary wet-weather accident rate at this type of site. The report recommends (1) compliance with the superelevation values for various degrees of curvature and speed in the AASHTO design guides and (2) attention to roadway geometry, signing, and maintenance practices to reduce severe maneuvers in the vicinity of curves. It should be of equal value to those responsible for the geometric design of new highways and those responsible for safety improvements at high accident locations.

Various factors have contributed to the rise in the number and severity of highway accidents, with attendant loss of life, injury, and property damage. As a result of the greater than normal accident experience at several downgrade curve sites, Project 1-14 was initiated to investigate the particular portion of the over-all accident problem involving skidding on highway sections containing the combination of horizontal curvature and vertical grade. The objective was to develop guidelines for highway geometries and pavement surface characteristics to ensure adequate vehicle control during anticipated maneuvers on such highway sections.

To examine the factors that influence safe operation of automobiles on highway sections with combined curvature and grade, the University of Michigan, Highway Safety Research Institute researchers divided the project into the following interrelated tasks: (a) accident data analysis, (b) mathematical vehicle simulation studies, (c) pavement surface drainage studies, and (d) field site investigations. Accident records for several years from the Ohio and Pennsylvania Turnpikes were examined for influences of curvature and grade, both separately and in combination. There did not appear to be a particularly high accident experience associated with downgrade curves, but the accident rate on curves of about 1° on the Ohio Turnpike was more than twice the over-all rate. Wet-pavement accidents were also definitely overrepresented on curves of about 1°. Simulation and analytical studies of a wide variety of vehicle, tire, road surface, geometric, and maneuver combinations were conducted to determine operating conditions that can lead to loss of control and the onset of skidding. It was determined that drivers are not likely to lose control of their vehicles on curve-grade sites unless they attempt severe maneuvers on slippery road surfaces with fair to poor tires.

From a review of previous research it was determined that pavement width and cross slope are the primary factors affecting pavement surface drainage. The thickness of water film on a long-radius curve, with a two-lane roadway and paved shoulder sloping in the same direction, can be almost twice that on a crowned tangent section with the same cross slope. It was determined that the two high accident field sites investigated had cross slopes of 0.0156 ft/ft and were located on 1° curves. In both cases, two paved lanes were sloped in the same direction.

The essential finding from the combined accident analysis, simulation studies, surface drainage studies, and field investigations is that drainage of the pavement surface is a very important consideration that is sometimes overlooked in pavement cross-section design. Water thickness on the pavement has a critical influence on the friction available at the tire-pavement interface and thus on the safe operation of vehicles. Tire hydroplaning is commonly considered to be the primary adverse effect from excess water on the pavement. In actuality, complete hydroplaning is probably a rare occurrence. The vast majority of wet-weather skidding accidents undoubtedly occur as the result of water depths well below that needed for complete hydroplaning. Partial hydroplaning (degradation of tire-pavement friction as a consequence of the presence of water) is the most likely cause of higher than normal wet-weather accidents on long-radius curves with inadequate cross slope in relation to drainage length.

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James Soule, of the Highway Safety Research Institute, was instrumental in conducting the on-site investigations.

INFLUENCE OF COMBINED HIGHWAY GRADE AND HORIZONTAL ALIGNMENT ON SKIDDING

SUMMARY

The purpose of the research reported here was to develop tentative guidelines for highway geometrics and pavement surface characteristics to ensure adequate vehicle control during maneuvers on highway sections containing a combination of horizontal and vertical alignment. Accordingly, the study tasks were to (1) examine the factors that influence safe operations on highway sections having combined curvature and grade; (2) determine those operating conditions that define the onset of skidding; (3) evaluate by accident data analysis, simulation, and field studies the factors involved in skidding; and (4) suggest measures for alleviating skidding accidents and recommend additions or modifications to current AASHTO design policies.

Accident records from the Ohio and Pennsylvania Turnpikes were examined for influences of curvature and grade, both separately and in combination. The analysis of the turnpike accident data shows that the Pennsylvania Turnpike accident rate is not dependent on grade, but does increase with increasing curvature. The Ohio Turnpike data show no significant accident dependence on either grade or curvature, except that a specific 1° curve on a 3-percent downgrade has a very high accident rate. This accident history appears to be associated to a high degree with wet pavement, and to a less degree with heavily worn tires. All 1° curves on the Ohio Turnpike have a high incidence of wet-pavement accidents.

Simulation and analytical studies of a wide variety of vehicle, tire, road surface, geometric, and maneuver combinations were conducted to define and evaluate operating conditions leading to loss of control and the onset of skidding. The maximum safe velocities for various operating conditions were evaluated for (1) equilibrium cornering, (2) lane changes, and (3) lane changing combined with braking. A lane-change maneuver was shown to be a critical condition at curve sites; it could result in loss of control at normal highway speeds for passenger vehicles with half-worn tires operating on payments with a skid resistance of $SN_{40} = 30$. In an emergency lane change and braking maneuver on an $SN_{40} = 30$ pavement, loss of control was shown to occur at approximately 60 mph, independent of grade and curvature, when vehicles were equipped with half-worn tires. From the simulation results, it was concluded that highway curves and sites having combined curvature and grade require greater pavement skid resistance than corresponding tangent sections as a safety margin against emergency maneuvers. The over-all findings of the simulation studies indicate that drivers are not likely to lose control of their vehicles on curve-grade sites unless they are attempting to perform severe maneuvers on slippery road surfaces with fair-to-poor tires. The analytical and simulation work performed in this study showed grade to be a roadway factor of small influence in determining skid resistance requirements.

Two sections of highway with high accident rates were selected and subjected to an indepth evaluation to determine accident causation factors. One of the selected sites was the high-accident site on a 1° curve with 3-percent downgrade on the Ohio Turnpike. The other site was located on I-95 near Fredericksburg,

Va. Likely causes for a high degree of maneuvering exist at the Virginia site because of an interchange with US 1 at this site. During this study, methods for evaluating problem sites were developed and used to conclude that (1) a pavement surface drainage problem exists at the problem site selected on the Ohio Turnpike; and (2) many factors—including pavement surface drainage, short speed-change lanes, insufficient sight distance, and obstructed signs—contribute to the high accident rate at the site selected in Virginia. Further evaluation of the pavement surface drainage problem indicates that water depth on a pavement is primarily a function of drainage length (pavement width) and cross slope (superelevation or crown). Consequently, during wet weather, pavement skid resistance available for emergencies is generally less on long radius multi-lane curves than on tangents because of greater pavement width and low superelevation. Grade is a secondary factor in determining pavement water depth.

On the basis of the combined findings from (1) an extensive analysis of accident data, (2) computer simulation studies, and (3) an indepth field investigation of two high-accident sites, it has been concluded that drivers are not likely to lose control of their vehicles on curve-grade sites unless they are attempting to perform severe maneuvers on slippery road surfaces with fair-to-poor tires. The AASHTO design procedures—as described in *A Policy on Geometric Design of Rural Highways, 1965* (GDRH) and *A Policy on Design of Urban Highways and Arterial Streets, 1973* (DUHAS)—provide a practical method for arriving at reasonable geometric designs for sites with combined horizontal curvature and vertical grade, provided (1) the selected values of superelevation are large enough to result in adequate pavement surface drainage and (2) the pavement skid resistance is sufficient for anticipated vehicle maneuvering. However, misinterpretation of the AASHTO design procedures has resulted in design and construction of long-radius curves with inadequate superelevation for surface drainage that contributes to an extraordinary wet-weather accident rate at this type of site. The report recommends compliance with the design superelevation values for various degrees of curvature and design speeds found in Tables III-7 to III-10 in (GDRH) and attention to roadway geometry, signing, and maintenance practices to reduce severe maneuvers on curves.

A major premise of these recommendations is that the pavement skid resistance at a given site should be adequate for the characteristics of the site. Accordingly, a formula has been developed for determining skid resistance requirements as a function of site geometrics, cross-section drainage properties, the traffic speed distribution, and minimum tire traction properties. Also, a rationale is presented for defining the maneuver demand potential along the length of the roadway as a highway design aid. To aid in determining improvements to be made at a high-accident site, a form has been developed to record the pertinent roadway factors.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

This report presents findings, recommendations, and conclusions developed by the Highway Safety Research Institute (HSRI) of The University of Michigan for the National Coöperative Highway Research Program (NCHRP) in a project entitled: "Influence of Combined Highway Grade and Horizontal Alignment on Skidding." This project deals with that portion of the over-all accident problem involving vehicle operation on highway sections containing both curvature and grade (upgrade or downgrade). The principal objective of this research was to develop tentative guidelines for highway geometrics and pavement surface characteristics to ensure adequate vehicle control during maneuvers on highway sections with combined vertical and horizontal alignment.

The specific tasks were to:

1. Examine analytically the roadway and vehicle factors that influence the safe operation of modern passenger automobiles on highway sections containing a combination of horizontal alignment and vertical alignment, with emphasis on the downgrade horizontal curvature condition. Specifically, the following parameters and variables are to be included in this analysis:
   a. Roadway—grades, superelevation rate and runoff, radius and type of horizontal alignment, pavement surface properties and conditions, drainage.
   b. Vehicle and Operation Characteristics—operating speeds and lateral acceleration; braking and longitudinal acceleration; weight, geometry, suspension, and related factors; tire characteristics and conditions.

High-level mathematical simulation techniques for analyzing the operation of automobiles with varying vehicle parameters under roadway conditions have been developed through research in other programs and verified by full-scale tests. Because of this fact—coupled with cost constraints—the development of new models is not anticipated during this project.

2. Determine those combinations of speed, roadway geometrics, and pavement conditions that define the onset of skidding for modern passenger automobiles.
3. Evaluate the results of tasks 1 and 2 by one or more of the following methods:
   a. Comparison with accident experience and roadway characteristics.
   b. Physical simulation.
   c. Field studies.
   d. Other.
4. Suggest measures for alleviating skidding accidents on highway sections containing a combination of horizontal and vertical alignment and prepare recommended additions or modifications to current AASHTO design policy to accommodate anticipated vehicle maneuvers on this type of highway section.

A plan was adopted which addressed the specific objectives by dividing the research into six research tasks. These tasks and the type of work performed in each task are briefly summarized as follows:

1. *Accident Data Analysis*—Accident data files for the Ohio and Pennsylvania Turnpikes were established and interrogated to obtain a relationship between horizontal and vertical alignment and accident experience.
2. *Computer Simulation Studies*—The Highway-Vehicle-Object Simulation Model/(HVOSM) (*1*) was applied to determine those roadway and vehicle factors leading to loss of control and the onset of skidding on sections of highway with combined vertical and horizontal alignment. Both a pilot simulation study for screening many factors and a full-scale simulation study were conducted. The maximum safe velocities, subject to operating conditions, for equilibrium cornering, lane changes, and lane changing combined with braking were evaluated.
3. *Field Investigation of Problem Sites*—Two sections of highway, one on the Ohio Turnpike and the other on I-95 in Virginia, both of which have combined horizontal and vertical alignment and high-accident experience, were selected and studied to identify those characteristics having potential for producing accidents at these sites.
4. *Analysis of Results of Tasks 1, 2, and 3*—The results of Tasks 2 and 3 were supplemented with analytical calculations of braking efficiency, cornering efficiency, and pavement drainage. The results of the accident data analyses (Task 1) were combined with results predicted by simulation to determine the conditions that cause loss of control.
5. *Formulation of Design Policy Recommendations*—Measures for reducing the incidence of passenger car accidents on sections of highway with combined horizontal alignment and upgrade and downgrade vertical alignment were derived from the findings of Tasks 1 through 4, and these measures were used to recommend modifications in current AASHTO design policy.
6. *Preparation of the Final Report*—The findings from the research approach defined by Tasks 1 through 5 are presented in Chapter Two of this report. These findings have been organized into the following categories:

- Accident Data Analysis.
- Vehicle Loss-of-Control Analysis.
- Pavement Drainage.
- Selection and Evaluation of Problem Sites.
- Design Policy Analysis.

Interpretations and applications of these findings are dis-

cussed in Chapter Three. Conclusions are stated in Chapter Four. Part II of this report contains several appendixes * providing detailed documentation of the work done to produce the findings presented in Chapter Two. (Part II is not published herewith but is contained in a separate volume, as submitted by the agency to the sponsors, and is available from NCHRP on a loan basis on request.)

It should be noted that towards the end of the contract period, emphasis was shifted from computer analysis to site evaluation studies because the simulation results and the accident data analysis indicated that vehicle drivers were not likely to lose control of their vehicles on curve-grade sites unless they were attempting to perform severe maneuvers on slippery road surfaces with fair-to-poor tires. Consequently, the problem sites were examined carefully to identify causes for severe maneuvers and relatively large water depths.

* A. Accident Data Analysis; B. Vehicle Dynamics on Curve-Grade Sections of Highway; C. The Influence of Grade and Curvature Alignment Combinations on Pavement Drainage; D. Field Evaluation of Highway Sites with High Accident Rates Having Combined Grade and Horizontal Curvature; E. The Influence of Grade on the AASHTO Curve Design Formula; F. Tentative Methods for Analysis of Accident-Causation Factors at Highway Sites with High Accident Rates; and G. Relationship Between Tire Shear Force and Tire Condition and Construction Factors.

CHAPTER TWO

FINDINGS

The findings and results of this program are presented in this chapter and are interpreted in Chapter Three to explain how they can be applied to the problem of maintaining vehicle control during maneuvers on highway sections containing a combination of horizontal and vertical alignment.

ACCIDENT DATA ANALYSIS

Synopsis of Accident Analysis Findings

The analysis of the turnpike accident data shows no evidence of effects that can be attributed to grades and curves in combination. The Pennsylvania Turnpike accident rate is not dependent on grade, but does increase with increasing curvature. The Ohio Turnpike shows no significant accident dependence on either grade or curvature, except that a specific 1° curve on a 3-percent downgrade has a very high accident rate. This accident history appears to be highly associated with wet pavement, and to be associated to some extent with heavily worn tires. All 1° curves in Ohio have a high incidence of wet-pavement accidents. Curves within the range of 0°44′ to 1°49′ in Pennsylvania also have a somewhat higher incidence of wet-pavement accidents than do curves of other curvatures.

Turnpike Accident Data Studies

Effects of Horizontal and Vertical Alignment on Accident Rates

The primary objective of the accident data analyses performed in this study was to determine the extent to which horizontal and vertical alignment, both singly and in combination, influence the accident rate of a highway. These analyses were facilitated by acquiring data on the accidents produced on the main traffic-ways of the Ohio and Pennsylvania Turnpikes. These highways have grades ranging from −3 to +2 percent on the Ohio Turnpike and from −3 to +3 percent on the Pennsylvania Turnpike. Curves on the two highways are limited to maximum curvatures of 2°30′ in Ohio and 6° in Pennsylvania. The Pennsylvania accident data cover a 2½-year period starting in 1966, and consist of records on 9,822 mainline accidents. Beginning in 1966, 4½ years of highway operations on the Ohio Turnpike yielded 5,553 mainline accidents.

Traffic counts were derived from the toll records. Information existed in sufficient detail to permit traffic exposure to be computed for each point on the highway.

Vertical alignment was combined with each accident record and merged with the traffic data. Similarly, horizontal alignment was also merged with both the accident records and traffic data.

The two sets of data—exposure and accident—permitted a derivation of accident rates with respect to both horizontal and vertical alignment. The analytic technique used was dummy variable multiple regression on stratified levels of vertical and horizontal alignment. Appendix A in Part II (available on loan) contains a detailed discussion of these regression models and the results obtained from their use.

Although both grade and curvature are continuous variables, their distribution on the turnpikes is not continuous. Furthermore, the quantity of data to be analyzed did not justify high resolution in the treatment of either parameter. For these reasons, grade was stratified into 7 levels, and horizontal alignment into 8 to 13 levels. The regression models provide additive estimates of the contribution to the accident rate that derive from horizontal and vertical alignment by using the data from all of the geometric combinations to estimate the incremental effect of each parameter.

TABLE 1

SUMMARY OF REGRESSION MODELS—ALL ACCIDENTS

	OHIO				PENNSYLVANIA			
Treatment of Horizontal Alignment	ρ^2	Standard Error of Regression	Rank	% Cells Outside Confidence Interval (95%)	ρ^2	Standard Error of Regression	Rank	% Cells Outside C.I.
Curvature 8 levels	0.6488	0.0067	2	11.4	0.5989	0.0080	3	13.7
Curvature 11 levels	------	------	-	----	0.6731	0.0064	2	16.0
Super-elevation	0.3239	0.0111	3	4.2	0.3540	0.0132	4	13.3
Side force factor f	0.6825	0.00652	1	11.4	0.7445	0.0038	1	23.2

The two highways have quite different over-all accident experience. On the Ohio Turnpike the over-all accident rate is 96 accidents per 10^8 veh-mi, whereas the corresponding rate on the Pennsylvania Turnpike is 148. This difference, reflected in the results of the regression models, makes highway-to-highway comparisons difficult to interpret. The problem is compounded by the use of different superelevation policies on the two highways. Thus, horizontal alignment is not defined completely by curvature alone. Because the regression of accident rate against curvature produced results that differed on the two highways, two additional models were used to describe the horizontal alignment. The three models used were regression of accident rate against (1) curvature, (2) superelevation rate, and (3) the portion of D'Alembert force due to lateral acceleration, which must be provided by pavement skid resistance (note that item (3) is sometimes referred to as "side friction factor" in AASHTO design policy (*2, 3*); see also Eq. 6). The latter was computed from curvature, superelevation rate, and speed equal to the posted legal limit. This quantity will be called the "side force factor," and the symbol f will be used to represent this quantity.

Table 1 provides a summary assessment of the regression models. The square of the multiple correlation coefficient, ρ^2, indicates the proportion of the variability in the data that is explained by the regression model. Thus the model with 8 levels of curvature explains 65 percent of the variability in Ohio and 60 percent in Pennsylvania, whereas the use of 11 levels of curvature in Pennsylvania explains 67 percent of the variability. The superelevation rate models were relatively unsatisfactory on both highways and of little value in comparing highways. The side force factor provided the highest correlation and explained approximately 70 percent of the variability.

The expected accident rate (based on the coefficient of the regression), the observed rate, the difference (residuals), and the 95-percent confidence intervals about the expected rate were computed for each combination of grade and horizontal alignment.

Acident-causation factors not explained by the additive alignment model would be expected to result in observed rates outside the confidence intervals with a probability of 0.05. Therefore, such occurrences would be expected in 5 percent of the combinations of grade and horizontal alignment. This proportion was exceeded in all models by a factor that indicates significant unidentified "error" sources. The individual cells having residuals representing real differences as opposed to chance consequences of random error can not be uniquely identified. Interaction between grade and horizontal alignment is no more significant than when each is considered separately.

The results of the regression models are given in detail in Appendix A (Part II), and the principal findings are depicted graphically in Figures 1 through 4 for the 8-level curvature model applied to the Ohio data and the 11-level model applied to the Pennsylvania data for tangent sections with little or no grade. Figures 5 through 8 show the results for the side-force-factor model, also for tangent sections with little or no grade. Results are given in each figure for all accidents and for single-vehicle and wet-pavement accidents.

The regression analysis indicates no statistically significant and problematical dependence of accident rate on grade except at the steeper downgrades (—2.5 to —3 percent) in Ohio. On the Pennsylvania Turnpike, there are moderate but significant reductions of single-vehicle accident rates on the steeper upgrades; on wet-pavement accidents on downgrades the reduction rate is about 1 percent. Both turnpikes show an accident dependence on curvature and side force factor. The models of Ohio Turnpike experience have a very high peak in accident rates at 1° curves and the equivalent f of 0.043. The accident rate in Ohio is not significantly dependent on other values of curvature or f. The Pennsylvania data exhibit an increasing accident rate with increasing curvature and with increasing f, but do not exhibit a high peak on 1° curves, as is the case in Ohio. Although the Pennsylvania Turnpike has locations with higher side force factors as well as higher curvatures than the Ohio Turnpike, the accident rates are higher in Pennsylvania than in Ohio at all curvatures and side force values. Thus, the side-force-factor model fails to explain the substantial accident rate differences between the two highways.

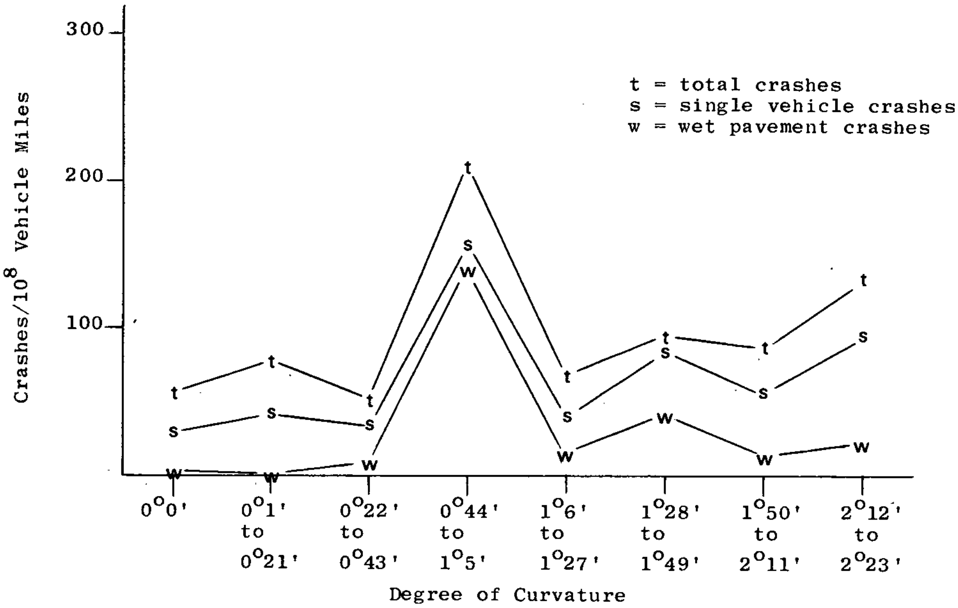


Figure 1. Curvature model—expected relationship between curvature and crash rate using Ohio Turnpike data (grade = ±0.6%).

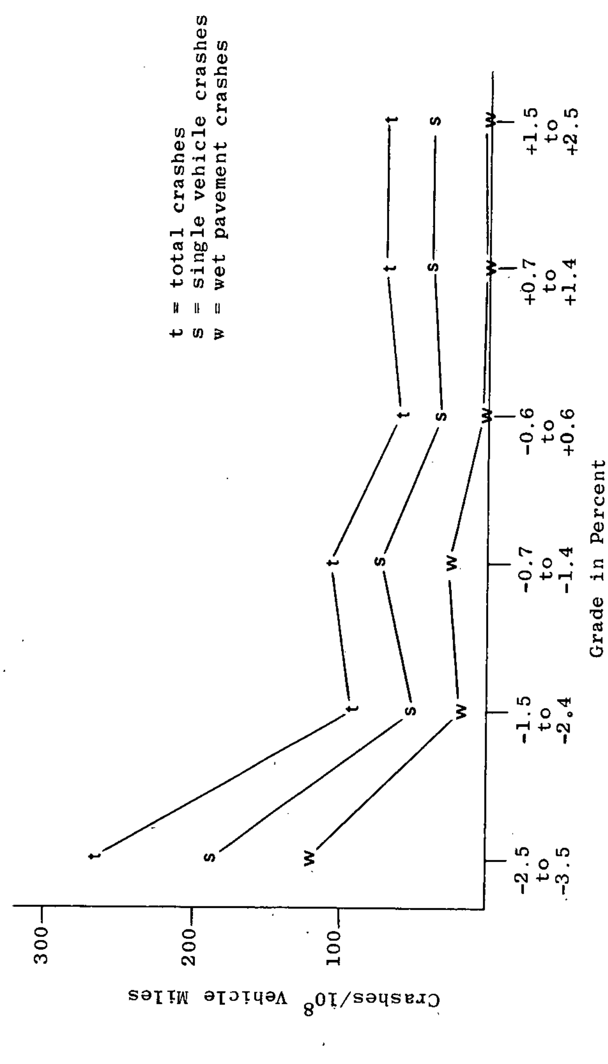


Figure 2. Curvature model—expected relationship between grade and crash rate using Ohio Turnpike data (curvature = 0°).

It is particularly noteworthy that there is a very high accident-rate site on the Ohio Turnpike. The intersection of the high-accident downgrade and high-accident curvature (grade = —2.5 to —3 percent and curvature = 0°44′ to 1°5′) is the only cell with an observed accident rate higher than the confidence interval of the expected accident rate. Furthermore, the 34 accidents in this cell all occurred in the westbound lanes between mileposts 166.4 and 166.6. This location is a 1° curve on a 3-percent downgrade. The accident rate in this 0.2-mile segment was 665 accidents/10^8 veh-mi over the 4½-year period covered by the data, as compared to an average of 95.9 for the entire highway. Later data supplied by the Turnpike Commission for the same site indicate that from July 1970 to April 1973—a 34-month period subsequent to the 4½-year period—the accident rate was 559 accidents/10^8 veh-mi. The site has continued to have a high accident record. Since the curvature is rather modest, the location was selected as a field study site and the findings are discussed later under "Evaluation of the Ohio Turnpike Site."

Environmental Factors

Several factors were examined relative to their association with accident rate and grade and curvature; namely, surface conditions, number of vehicles involved in the accident, and illumination. Weather was not included because it was found that surface conditions are a surrogate for weather.

Table 2 gives the distribution of accidents by surface condition for each stratum of curvature and grade on the Ohio Turnpike. It is important to observe that an abnormally high proportion of the accidents produced on curves within the range of 0°44′ to 1°5′ and on downgrades of

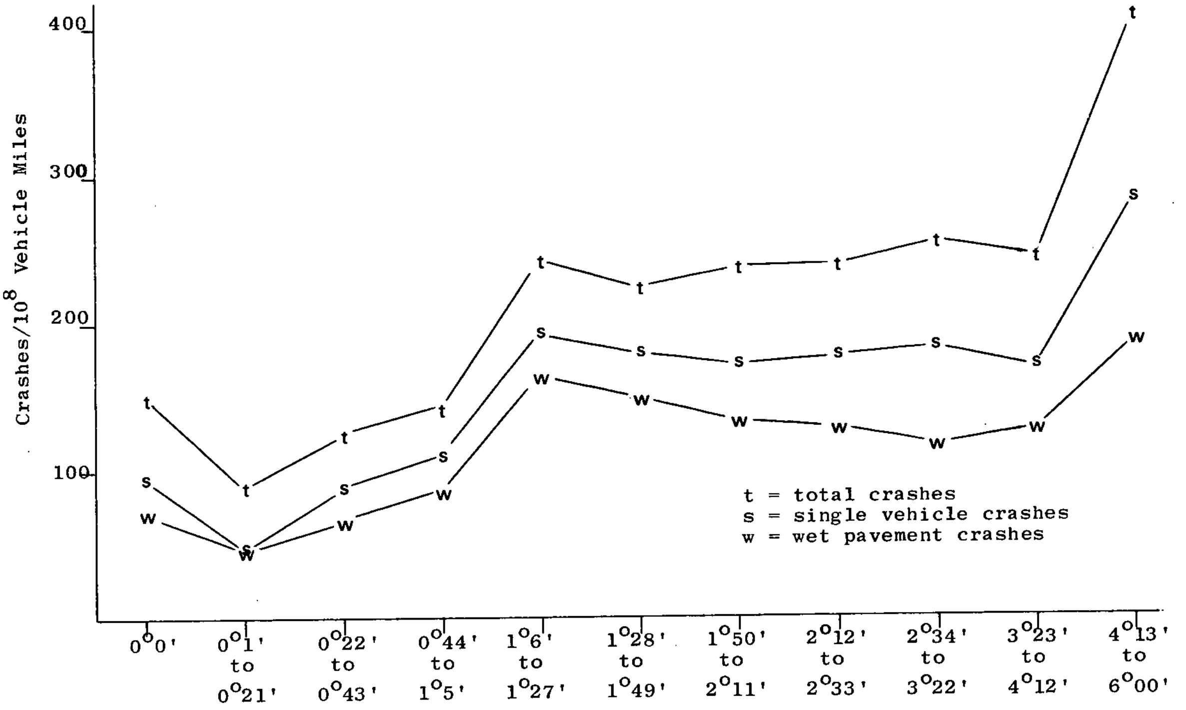


Figure 3. Curvature model—expected relationship between curvature and crash rate using Pennsylvania Turnpike data (11 levels of curvature; grade = ±0.6%).

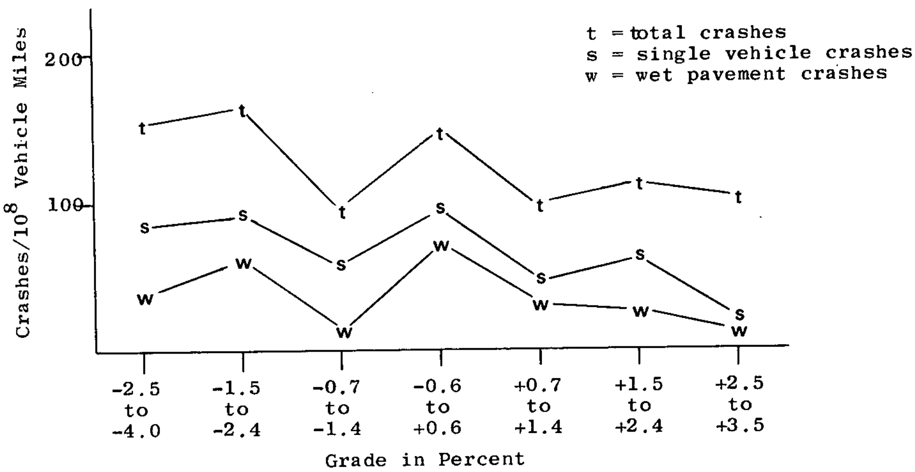


Figure 4. Curvature model—expected relationship between grade and crash rate using Pennsylvania Turnpike data (11 levels of curvature; curvature = 0°).

2.5 to 3.5 percent occurred on wet pavements. Wet-pavement accidents are overrepresented in road sections with these alignments by nearly 2 to 1. (The curvature and grade strata with high "wet" incidence contain the site selected for field investigation.) In addition, tangent sections of the Ohio Turnpike have a lower proportion of wet-pavement accidents than the remainder of the road. Corresponding data for the Pennsylvania Turnpike are given in Table 3. The relative incidence of wet-surface accidents does not vary significantly with grade in Pennsylvania. A high proportion of wet-weather accidents does occur on curves 0°44′ to 1°49′ on the Pennsylvania Turnpike.

Table 4 classifies the Ohio Turnpike accidents occurring on the various levels of curvature and grade into single- and multi-vehicle accidents. Note that the incidence of single-vehicle accidents is higher in the same two strata that exhibited a high proportion of wet-surface accidents. Although the data in Table 5 show some variation for single-vehicle accidents on the Pennsylvania Turnpike, no consistent pattern is observed.

Both turnpikes have the highest relative incidence of

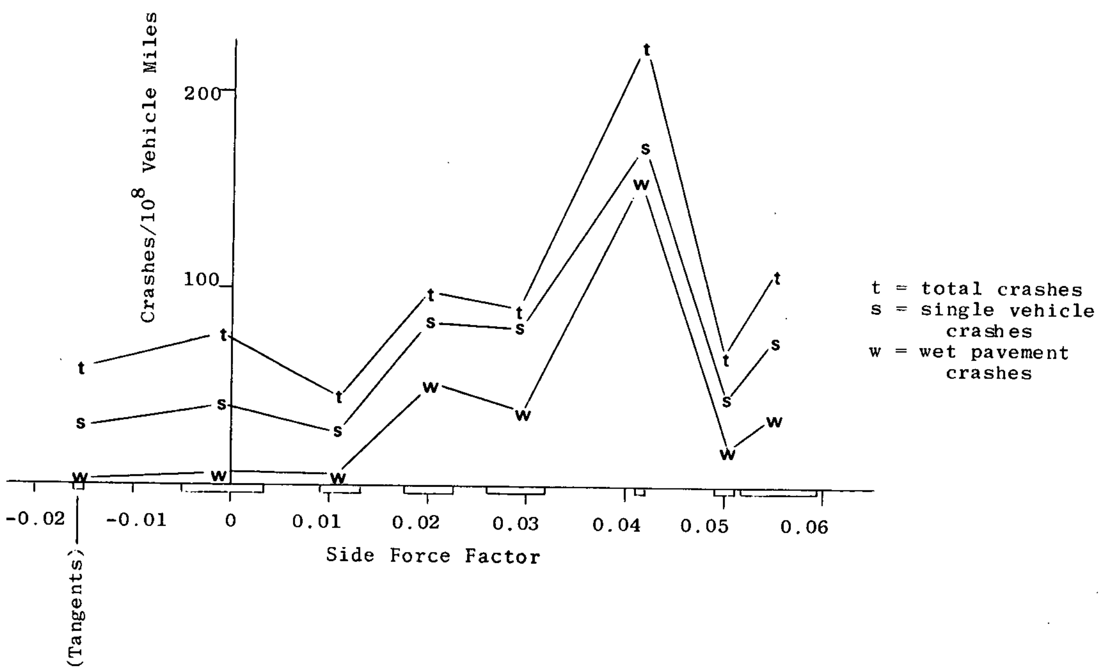


Figure 5. Side force factor model—expected relationship between side force factor and crash rate using Ohio Turnpike data (intervals of side force factor used for side force model indicated by horizontal bar below abscissa; grade = ±0.6%).

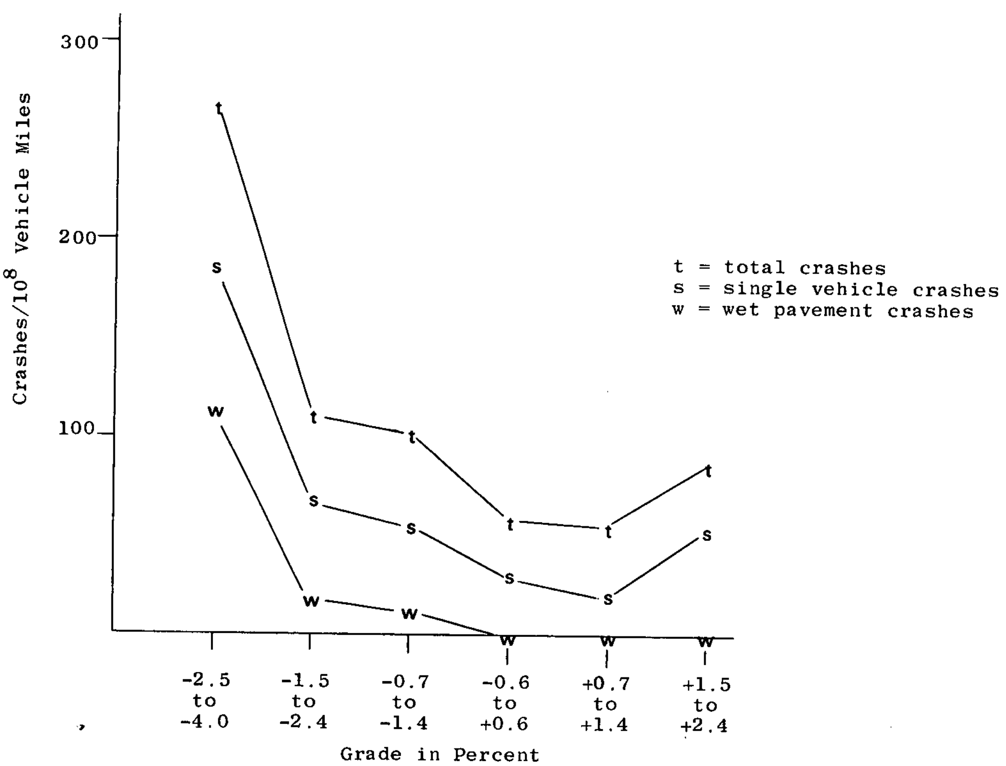


Figure 6. Side force factor model—expected relationship between grade and crash rate using Ohio Turnpike data (curvature = 0°).

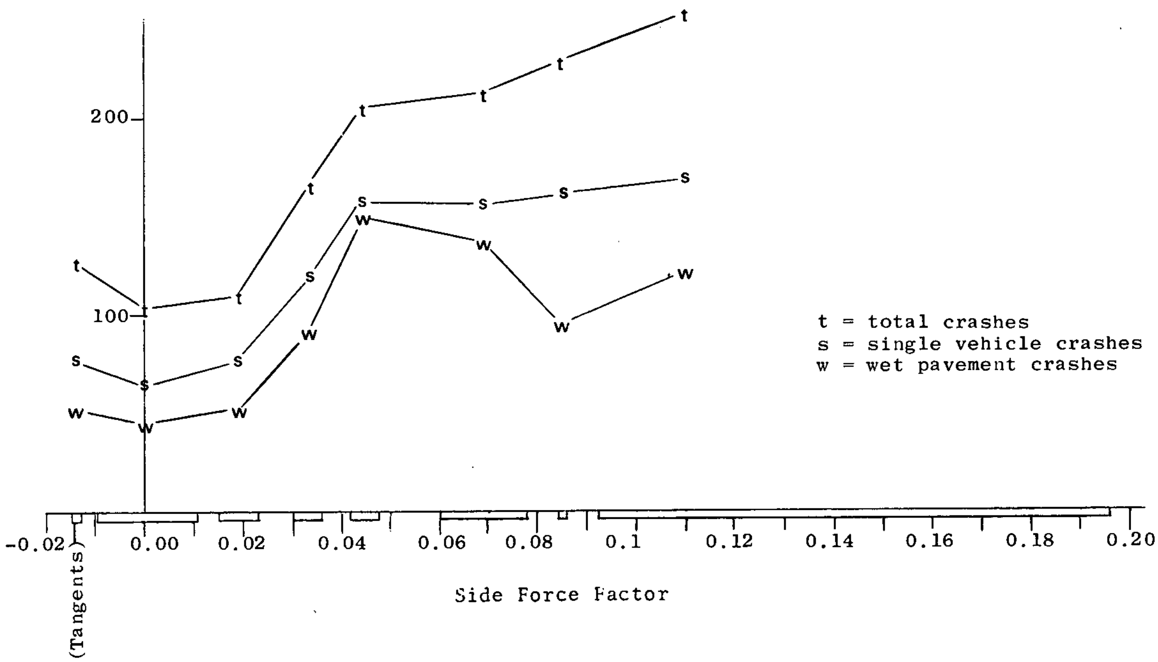


Figure 7. Side force factor model—expected relationship between side force factor and crash rate using Pennsylvania Turnpike Data (intervals of side force factor used for side force model indicated by horizontal bar below abscissa; grade = ±0.6%).

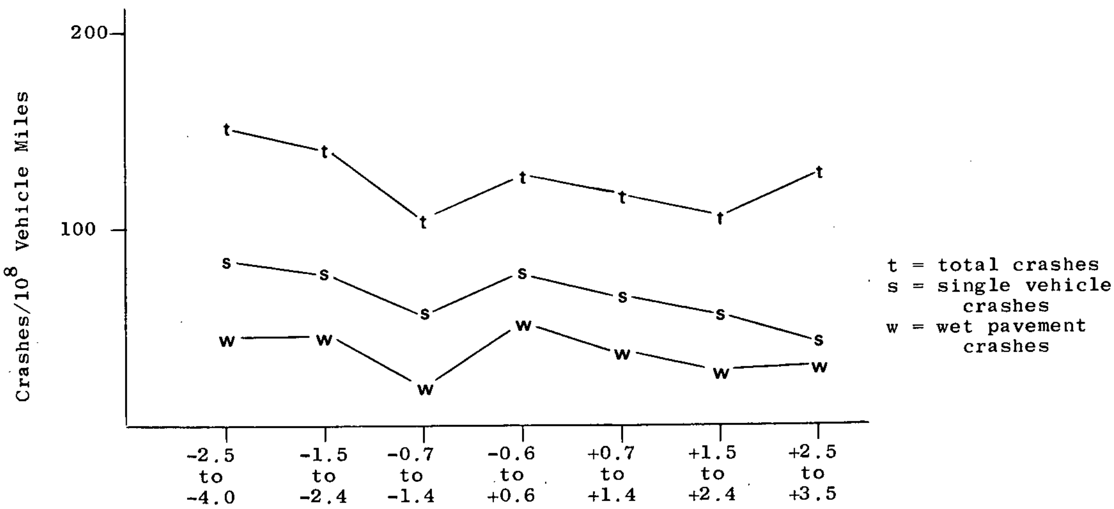


Figure 8. Side force factor model—expected relationship between grade and crash rate using Ohio Turnpike data (curvature = 0°).

wet-pavement and single-vehicle accidents on curves of about 1°. Both types of accidents could be expected to be associated with loss of control from limitations of the tire-road interface.

A distribution of accidents categorized by the presence of daylight or darkness is given in Tables 6 and 7. Except for a greater incidence of crashes occurring in darkness on tangents of the Ohio Turnpike, very little variation as a function of alignment exists on either turnpike.

Causative Factors at High-Accident Sites

The highway alignment geometrics identified as high-accident sites by the regression analysis are the 1° curves and the 2.5 to 3 percent downgrades on the Ohio Turnpike and the 4°13′ to 6° curves on the Pennsylvania Turnpike. One-way analyses of variance of numbers of accidents at these alignments were run against other alignments, using the variables in each file that are related to causation as control variables. Summaries of the results are given in

TABLE 2

ACCIDENT EXPERIENCE BY SURFACE CONDITION—OHIO TURNPIKE

Degree of Curvature	Number of Accidents	Percent: Dry	Wet	Other*
0°0'	3,317	61.5	18.5	20.0
0°1'-0°21'	619	56.7	27.6	15.7
0°22'-0°43'	621	54.4	32.2	13.4
0°44'-1°5'	616	34.9	53.4	11.7
1°6'-1°27'	96	60.4	27.1	12.5
1°28'-1°49'	73	56.2	32.9	11.0
1°50'-2°11'	78	55.1	21.8	23.1
2°12'-2°33'	133	47.4	21.8	30.8
Total	5,553	56.7	25.4	17.9
Grade in Percent				
+1.5 to +2.4	649	57.5	22.2	20.3
+0.7 to +1.4	547	55.9	23.6	20.5
-0.6 to +0.6	2,879	59.9	24.8	15.2
-1.4 to -0.7	642	52.8	25.7	21.5
-2.4 to -1.5	708	49.4	29.2	21.3
-3.5 to -2.5	83	36.1	49.4	14.5
Total	5,553	56.7	25.4	17.9

*The "other" category consists largely of snow/ice conditions.

TABLE 3

ACCIDENT EXPERIENCE BY SURFACE CONDITION—PENNSYLVANIA TURNPIKE

Degree of Curvature	Number of Accidents	Percent: Dry	Wet	Other*
0°0'	4,479	53.3	29.5	17.2
0°1'-0°43'	569	51.7	29.2	19.2
0°44'-1°49'	1,595	38.1	51.2	10.8
1°50'-2°33'	1,310	38.4	43.5	18.1
2°34'-3°22'	1,136	43.8	35.6	20.6
3°23'-4°12'	434	39.4	42.4	18.2
4°13'-4°12'	75	48.0	30.7	21.3
5°00'-6°00'	224	55.8	33.0	11.2
Total	9,822	47.1	36.2	16.7
Grade in Percent				
+2.5 to +3.5	1,615	49.8	32.3	17.9
+1.5 to +2.4	1,016	46.4	36.0	17.6
+0.7 to +1.4	1,007	50.1	36.0	13.9
-0.6 to +0.6	2,158	46.4	40.0	13.6
-1.4 to -0.7	1,009	51.7	30.5	17.8
-2.4 to -1.5	1,198	46.4	37.4	16.2
-3.5 to -2.5	1,819	41.8	37.7	20.5
Total	9,822	47.1	36.2	16.7

*The "other" category consists largely of snow/ice conditions.

Tables 8 through 10. The significance level given in each table as a percent is the probability that differences as great as those observed would result from chance alone. If the significance level is less than 5 percent, the differences are usually interpreted as real.

The results shown in Table 8 for weather, light conditions, and surface conditions are consistent with earlier observations made in this section. The variable tabulated as "primary cause" listed on the accident report contains a higher incidence of entries implicating defective tires on 1° curves than on the remainder of the road. This result is noteworthy and will be discussed later. Defective tires were also listed frequently as the "unsafe action."

On the 2.5- to 3-percent downgrades in the Ohio Turnpike (Table 9), rain and wet pavements are frequently implicated in the accident record. No primary causation codes—such as tires, vehicle defects, speed, drinking, inattention, etc.—were indicated with significantly different frequencies. Inattention was listed as a personal factor significantly less frequently in accidents occurring on downgrades. Fixed-object accidents were overrepresented.

Table 10 gives the analysis of variance for curves within the range 4°13′ to 6°, compared with tangents and curves up to 0°43′ on the Pennsylvania Turnpike. Weather, illumination, and surface conditions were not significant, whereas they were on the Ohio Turnpike. Speed too fast, failed to signal, and fatigue were frequently listed causes on the sharper curves. Defective tires were less frequently listed. The findings categorized by accident type are similar to those obtained in Ohio except for the higher incidence of head-on collisions occurring in Pennsylvania.

Eighty percent of the accidents on the 4° to 6° curves of the Pennsylvania Turnpike are also on grades of from 2.5 to 3.5 percent, nearly equally divided between upgrades and downgrades. This finding reflects the nature of the topography where the sharp curves occur.

The high incidence of wet-pavement accidents occurring on 1° curves in Ohio has been noted. Examination of the individual accident reports filed for accidents occurring at the selected field study site in Ohio during the 4½-year study period and in the subsequent years shows a high incidence of wet-pavement accidents occurring with tires with little or no tread. At least on the Ohio Turnpike, it appeared that insufficient tread depth might be the principal tire "defect."

The relationship between defective tires and wet pave-

TABLE 4

SINGLE- VERSUS MULTI-VEHICLE ACCIDENTS—OHIO TURNPIKE

Degree of Curvature	Number of Accidents	Percent: Single Vehicle	Multi-Vehicle
0°0'	3,317	66.4	33.6
0°1'-0°21'	619	62.4	37.6
0°22'-0°43'	621	69.2	30.8
0°44'-1°5'	616	75.3	24.7
1°6'-1°27'	96	67.7	32.3
1°28'-1°49'	73	74.0	26.0
1°50'-2°11'	78	74.4	25.6
2°12'-2°33'	133	64.7	35.3
Total	5,553	67.4	32.6
Grade in Percent			
+1.5 to +2.4	649	64.4	35.6
+0.7 to +1.4	547	66.2	33.8
-0.6 to +0.6	2,879	68.7	31.3
-1.4 to -0.7	642	65.6	34.4
-2.4 to -1.5	708	67.2	32.8
-3.5 to -2.5	83	73.5	26.5
Total	5,553	67.4	32.6

TABLE 5

SINGLE- VERSUS MULTI-VEHICLE ACCIDENTS—PENNSYLVANIA TURNPIKE

Degree of Curvature	Number of Accidents	Percent: Single Vehicle	Multi-Vehicle
0°0'	4,479	52.9	47.1
0°1'-0°43'	569	56.4	43.6
0°44'-1°49'	1,595	69.7	30.3
1°50'-2°33'	1,310	65.1	34.9
2°34'-3°22'	1,136	64.3	35.7
3°23'-4°12'	434	65.9	34.1
4°13'-4°59'	75	53.3	46.7
5°00'-6°00'	224	60.3	39.7
Total	9,822	59.5	40.5
Grade in Percent			
+2.5 to +3.5	1,615	46.6	53.4
+1.5 to +2.4	1,016	62.4	37.6
+0.7 to +1.4	1,007	59.7	40.3
-0.6 to +0.6	2,158	61.9	38.1
-1.4 to -0.7	1,009	61.3	38.7
-2.4 to -1.5	1,198	61.4	38.6
-3.5 to -2.5	1,819	62.8	37.2
Total	9,822	59.5	40.5

ment for the entire accident population of each turnpike is shown in Table 11. In Ohio, nearly twice as many defective tires appear in the wet-pavement accidents as in the dry-surface set, and a higher proportion of defective tires is found in wet-surface accidents than would be expected from the distribution of accidents. The differences are significant at the 0.0-percent level. Nearly the inverse is true in Pennsylvania, where the incidence of defective tires is considerably lower. The differences in "defective tires" in the two highways may be partly the result of accident file structure and differences in reporting protocol. Comparisons between highways with respect to causative factors may not be realistic.

VEHICLE LOSS-OF-CONTROL ANALYSIS

Types of Analysis

Computer simulation techniques and simplified theoretical analyses can be effectively employed to examine the roadway and vehicle factors that influence the safety of current automobiles operating on highways characterized by a combination of horizontal and vertical alignments. Both of these types of analysis have been used in this program.

The theoretical analysis provides insight into (1) vehicle braking as influenced by vehicle loading, geometry, brake proportioning, and pavement surface friction; (2) vehicle cornering as influenced by grade, superelevation, radius of curvature, velocity, pavement friction, tire characteristics, and vehicle geometry; and (3) the influence of braking while cornering. Two results from this analysis will be discussed in this section. They are (1) a working definition of "vehicle loss of control" and (2) a quasistatic analysis of cornering on a downgrade. A detailed presentation of the entire analysis is given in the first part of Appendix B in Part II.

The simulation study consisted of two parts—a pilot study to assess the importance of the many vehicle and roadway factors affecting vehicle cornering performance on a grade, and a parametric study to examine the influence of different surfaces, tires, grades, curvatures, superelevations, and vehicle types on the maximum speed at which the folowing three maneuvers could be performed: cornering under traction, cornering and lane changing, and cornering plus lane changing combined with braking. The Highway-Vehicle-Object Simulation Model (HVOSM) program (*1*) was used to perform this parametric study. Because the HVOSM program requires the input of coeffi-

TABLE 6

ACCIDENT EXPERIENCE BY ILLUMINATION—
OHIO TURNPIKE

Degree of Curvature	Number of Accidents	*Percent: Daylight	Darkness
0°0'	3,317	53.1	40.4
0°1'-0°21'	619	58.8	36.5
0°22'-0°43'	621	56.4	39.1
0°44'-1°5'	616	65.3	29.7
1°6'-1°27'	96	57.3	40.6
1°28'-1°49'	73	56.2	37.0
1°50'-2°11'	78	46.2	52.6
2°12'-2°33'	133	68.4	27.8
Total	5,553	55.8	38.5
Grade in Percent			
+1.5 to +2.4	649	59.3	41.6
+0.7 to +1.4	547	54.8	41.3
-0.6 to +0.6	2,879	53.5	39.8
-1.4 to -0.7	642	62.3	33.3
-2.4 to -1.5	708	60.6	35.3
-3.5 to -2.5	83	55.4	39.8
Total	5,553	55.8	38.5

*The daylight and darkness figures add to less than 100 because 5.6% of the accidents were at dawn/dusk.

TABLE 7

ACCIDENT EXPERIENCE BY ILLUMINATION—
PENNSYLVANIA TURNPIKE

Degree of Curvature	Number of Accidents	*Percent: Daylight	Darkness
0°0'	4,479	62.4	33.0
0°1'-0°43'	569	62.9	32.9
0°44'-1°49'	1,595	67.9	27.2
1°50'-2°33'	1,310	66.2	28.5
2°34'-3°22'	1,136	64.4	32.0
3°23'-4°12'	434	65.9	29.5
4°13'-4°59'	75	72.0	26.7
5°00'-6°00'	224	59.8	35.3
Total	9,822	64.2	31.2
Grade in Percent			
+2.5 to +3.5	1,615	68.0	27.6
+1.5 to +2.4	1,016	62.9	32.7
+0.7 to +1.4	1,007	63.2	31.3
-0.6 to +0.6	2,158	44.2	31.0
-1.4 to -0.7	1,009	59.8	36.6
-2.4 to -1.5	1,198	64.6	30.2
-3.5 to -2.5	1,819	63.8	31.6
Total	9,822	64.2	31.2

*The daylight and darkness figures add to less than 100 because 4.6% of the accidents were at dawn/dusk.

cient of friction data for given sets of tire and pavement conditions, an auxiliary program was written to accept separate inputs for general tire and pavement surface characteristics and to compute coefficient of friction values. Pavement surface characteristics were described in terms of skid number measured at 40 mph (SN_{40}) and skid number gradient with respect to speed. Auxiliary programs were also written to (1) calculate terrain tables suitable for representing superelevated curve/grade sites in the simulation model and (2) provide steering inputs to guide the simulated vehicle along a circular roadway while also being capable of changing lanes. These auxiliary programs and the results from the simulation study are treated in detail in the latter part of Appendix B (Part II). This section presents the analytical results, followed by a summary of the findings of the simulation study.

Results from the Simplified Analysis

A primary result, derived in part from the simplified analysis, is a definition of "loss of control." The following working definition of "loss of control" was adopted for use in this investigation. A driver (or the vehicle control system used in the simulation) has suffered a *loss of control* when either (1) an increase in steering angle no longer produces a higher path curvature ($1/R$) (referred to herein as "trajectory instability"), or (2) an increase in steer angle produces an unstable yaw acceleration (referred to herein as "directional instability").

In the first loss-of-control mechanism, the vehicle's response to steering inputs is commonly referred to as a "plow-out." It is characterized by a saturation of the lateral shear force capability of the front tires. The second loss-of-control mechanism is popularly referred to as "spin-out," and it is characterized by saturation of the lateral shear force capability of the rear tires. In this latter case, the front tires, which are still capable of producing additional side force, can be steered to produce forces that can not be balanced by the saturated rear tires. Consequently, the vehicle has an unbalanced yaw moment that tends to spin the vehicle around, thereby developing a large angle (called the sideslip angle) between the tangent to the path of the center of gravity of the vehicle and the direction of the vehicle's plane of symmetry. Both loss-of-control mechanisms are recognized readily when they occur in the simulation. The plow-out response is identified by an ever-increasing steer angle with no corresponding increase

TABLE 8

SUMMARY OF ONE-WAY ANALYSIS OF VARIANCE—OHIO TURNPIKE

Accidents on Curves of 0°44'-1°5' Compared to All Other Curvatures Including Tangents

Variable	Condition	Relative Incidence	Significance Level (%)
Weather	rain or sleet other	- high* - low	< 0.1
Light	dark dawn	- high - low	< 0.1
Surface Condition	wet others	- high - low	< 0.1
Primary Cause Listed on Acc. Report	defective tires, unsafe speed mech. failure, sleep	- high - low	< 0.1
Unsafe Personal Factors	drinking unskilled driver, sleep, inattention	- high - low	< 0.1
Unsafe Action	defective tires, unsafe speed for conditions lost control, failure to yield 1/2 roadway, crowding	- high - low	< 0.1
Accident Type	sideswipe, fixed object, ran-off-road rear end	- high - low	< 0.1

*The terms "high" and "low" refer to the relative number of accidents under the conditions listed. For example, in this table corresponding to the variable "Primary Cause Listed on Acc. Report," "defective tires" and "unsafe speed" are cited with relatively high frequency while "mechanical failure" and "sleep" are cited relatively few times.

in lateral acceleration. The spin-out is recognized by a dramatically divergent sideslip angle response.

A simplified, numerically oriented explanation of vehicle behavior in loss-of-control situations can be obtained by using the results of the quasistatic analysis of cornering on a downgrade (presented in Appendix B of Part II). This analysis will predict results comparable to those obtained by Zuk (*4*) for cases in which the maximum lateral shear force capability of the front and rear tires is equal. In addition, this analysis can be used to predict loss of control when the maximum lateral forces capable of being produced by front and rear tires are different. During a steady turn maneuver there are two equilibrium conditions to be satisfied, in addition to not violating the constraints implied by the maximum available forces at the tires. These conditions are a lateral-force balance and a yaw-moment balance. In a highly simplified analysis, these conditions are expressed as:

Lateral Force:

$$F_{YF} + F_{YR} = (W/g)(V^2/R) - We \qquad (1)$$

Yaw Moment:

$$a\,F_{YF} - b\,F_{YR} = 0 \qquad (2)$$

where:

F_{YF} = the lateral force from both front tires;
F_{YR} = the lateral force from both rear tires;
W = the weight of the vehicle;
R = the radius of the turn;
e = the superelevation;
a = the distance from the vehicle center of gravity to the front axle;
b = the distance from the vehicle center of gravity to the rear axle; and
g = the gravitational constant.

Note that grade does not enter into these simplified equations because grade has a negligible influence on steady turning performance for the range of grades found on most U.S. highways.

Quite clearly, the skid resistance of the road limits the maximum total lateral force available and, consequently, the maximum lateral acceleration implied by Eq. 1. However, the moment balance between front and rear tire forces must be satisfied if the vehicle is to be under control in a turn.

Simulation Findings

A pilot simulation study was performed to identify the highway and vehicle factors to be examined in a more detailed parametric study. The parametric study contained the following items:

1. Five types of road surfaces, representing different skid numbers and skid number gradients.
2. Three states of tire wear: new, half worn, and fully worn.
3. Three downgrades: 1 percent, 3 percent, and 6 percent.
4. Three curves: 1°, 3°, and 6°.
5. Three superelevations: −0.0156 ft/ft, 0.048 ft/ft, and 0.100 ft/ft.
6. Three vehicle types: small sedan, intermediate sedan, and station wagon.
7. Three maneuvers: cornering under traction, cornering and lane change, and cornering and lane change plus braking.

As indicated, only passenger automobiles were included; thus, the findings of the simulation analysis do not apply to trucks, busses, and recreation vehicles. Wind and road roughness effects were also not included.

The results of the parametric study are presented in terms of the maximum velocity above which loss of control will occur for the given operating conditions. In this study these maximum velocities were symbolized for each maneuver as follows:

V_{CR} = the limiting safe velocity for cornering with drive thrust applied as necessary to maintain constant velocity;

V_{LC} = the limiting safe velocity for a cornering vehicle which also performs a 9- to 12-ft lane change while drive thrust is applied to maintain a constant velocity; and

V_{LOC} = the maximum initial velocity from which a combined lane change and abrupt stop maneuver can be performed without loss of control.

To appreciate fully the results of this simulation study, certain implications of the three maneuvers should be made clear. First, the limiting factor in the constant-speed cornering maneuver is usually the amount of drive torque required to maintain constant velocity. The longitudinal slip required to produce a propulsive force on the rear drive wheels reduces the capability of the rear tires to produce a lateral force. As speed is increased, more longitudinal slip is required. Eventually an operating point is reached in which there is not enough lateral force available to maintain a yaw moment balance, and the vehicle spins out. The vehicle could execute the turn at a higher average speed if drive thrust were removed, with the vehicle, so to speak, "coasting."

In the lane-change maneuver the direction of the lane change (i.e., to the right or to the left) affects the likeli-

TABLE 9

SUMMARY OF ONE-WAY ANALYSIS OF VARIANCE—OHIO TURNPIKE

Accidents on Downgrade of -2.5%-3% Compared to All Other Grades Including Horizontal Sections

Variable	Condition	Relative Incidence	Significance Level (%)
Weather	rain others	- high* - low	< 0.1
Light			not sig.
Surface Conditions	wet dry	- high - low	< 0.1
Primary Cause			not sig.
Unsafe Action	unsafe speed for conditions failure to pass clearly	- high - low	3.9
Unsafe Personal Factors	inattention	- low	0.3
Accident Type	fixed object rear end, side swipe, ran-off-road	- high - low	0.1

*See footnote at bottom of Table 8 for the meaning of the terms "high" and "low."

TABLE 10

SUMMARY OF ONE-WAY ANALYSIS OF VARIANCE—PENNSYLVANIA TURNPIKE

Accidents on Curves of 4°13'-6° Compared with Curves of 0°0'-0°43'

Variable	Condition	Relative Incidence	Significance Level (%)
Weather			not sig.
Illumination			not sig.
Surface Conditions			not sig.
Offending Vehicle Movement (Intent)			not sig.
Primary Cause Listed on Acc. Report	speed too fast, failed to signal, driver drowsy or asleep	- high*	< 0.1
	followed too closely, defective tires, other, animal on road	- low	
Accident Type	head-on, side swipe, fixed object, non-collision	- high	0.1
	rear end, angle	- low	

*See footnote at the bottom of Table 8 for the meaning of the terms "high" and "low."

hood that the friction potential of the tire/surface interface will be exceeded. On a curve to the right, the simulation results indicate that greater instantaneous tire forces are required to change from the left lane to the right lane than to change from the right lane to the left lane. In the latter case, the acceleration developed in the curve helps to start the lane change (the driver can begin to "drift out"). But in the former case, the friction level of the tire/road interface is likely to be exceeded while trying to change to a smaller radius path. Clearly, the opposite is true on a curve to the left, where it is more difficult to change from the right to the left lane of the highway without exceeding the friction potential available. The lane change results presented here correspond to the more demanding condition.

In the third maneuver, lane changing plus braking, the lane change is made to the inside of the curve (the worst case) while the brakes are applied simultaneously to maintain 0.3-g longitudinal deceleration. For the slippery road conditions used in this study, the brake proportioning of most passenger vehicles is such that large front-wheel slip or even front-wheel lockup will occur in this maneuver. Thus the maximum side force capability of the front wheels will be reduced, and a plow-out type of response occurs at the velocity limit, V_{LOC}.

The simulation findings with respect to V_{CR} and V_{LOC} are summarized in Figure 9. These results show for the critical lane change plus braking maneuver the influence of pavement skid number (SN_{40}) and curvature on V_{CR} and V_{LOC} for a baseline set of conditions in which a typical sedan with half-worn tires is operated with $e = 0.0156$ ft/ft and $G = -6$ percent. It can be seen that, although curvature has a large influence on V_{CR}, it has only a small influence on V_{LOC}. Clearly, pavement skid number has a large bearing on these results. For example, in the case of a vehicle with half-worn tires, an SN_{40} value of 40 is needed to ensure that V_{LOC} is greater than 70 mph for a turn on a 3° curve. For 6° curves, it appears that an SN_{40} value of about 55 is needed to ensure that V_{LOC} is greater than 70 mph. For fully worn tires, even higher skid numbers would be needed. In fact, there is a direct trade-off between tire and pavement surface-characteristics because the HVOSM input is tire/pavement friction and the tire and pavement characteristics are combined in this study to compute the coefficient of friction values.

It was also found that grade had very little influence on V_{LOC}. In general terms, it may be said that the lane change plus braking maneuver was severe enough that grade and curvature had only a small influence on the results.

In a later section under "Value of the Margin of Safety for Emergency Maneuvers," the results presented in Appendix B for the V_{LC} are used to develop an approximate linear formula for predicting the value of SN_{40} needed to make successful lane changes at curve/grade sites. Discussion of this formula is deferred until that section. Nevertheless, it should be stated here that an important finding of the simulation study was that the lane-change maneuver was shown to be a critical condition that could result in loss-of-control situations at normal highway speeds. For example, as shown on Figure 10, for passenger cars operated with half-worn tires on 3° curves with 0.048 ft/ft superelevation, $V_{LC} = 66$ mph on a surface with $SN_{40} = 30$.

Comparable results using the simple point mass equation for cornering performance (see Eq. 8) are also shown on Figure 10. It is clear that using the point mass equation for predicting the cornering performance of an actual vehicle is far from conservative and could lead to a false sense of security.

TABLE 11

DEFECTIVE TIRES AS A CAUSATION FACTOR

	Ohio Turnpike			Pennsylvania Turnpike		
	All Acc.	Single Veh.	Multi-Veh.	All Acc.	Single Veh.	Multi-Veh.
Percent of Accidents on Wet Pavement	25.4	29.0	20.0	46.7	42.7	25.5
Percent of All Defective-Tire Accidents on Wet Pavement	44.3	44.3	54.5	19.4	20.2	10.3
Percent of Wet-Pavement Accidents with Defective Tires	19.2	24.7	5.1	2.7	3.6	0.4
Percent of Dry-Pavement Accidents with Defective Tires	10.0	16.0	1.2	8.1	14.5	1.5

PAVEMENT DRAINAGE ANALYSIS

Pavement drainage is an important consideration in cross-section design in that water depth has a critical influence on the friction available at the tire-road interface. Tire hydroplaning is commonly considered to be the primary adverse effect resulting from excess water on the pavement. In actuality, however, a complete hydroplaning, even with smooth tires, is probably a rare occurrence. The vast majority of wet-weather skidding accidents undoubtedly occurs as a result of water depths well below those needed for complete hydroplaning. Data obtained, for example, on a specific smooth tire (*5*) show that a water depth of 0.15 in. is required for complete hydroplaning wheel spindown at 60 mph, whereas the tire brake force coefficient becomes less than 0.05 at this same velocity at a water depth of 0.03 in. The primary consequence of excess water on the pavement, then, is a degradation in tire traction. The traction loss is almost always far short of that needed to produce hydroplaning; yet, the available traction is well below the range needed for safe driving.

Research on methods for predicting pavement water depth as a function of rainfall rate and pavement geometrics has been conducted at the Texas Transportation Institute (TTI), the Road Research Laboratory (RRL), and the Goodyear Tire and Rubber Company. The results of these research efforts are discussed in Appendix C. Gallaway et al (*6*) at TTI have developed a formula for

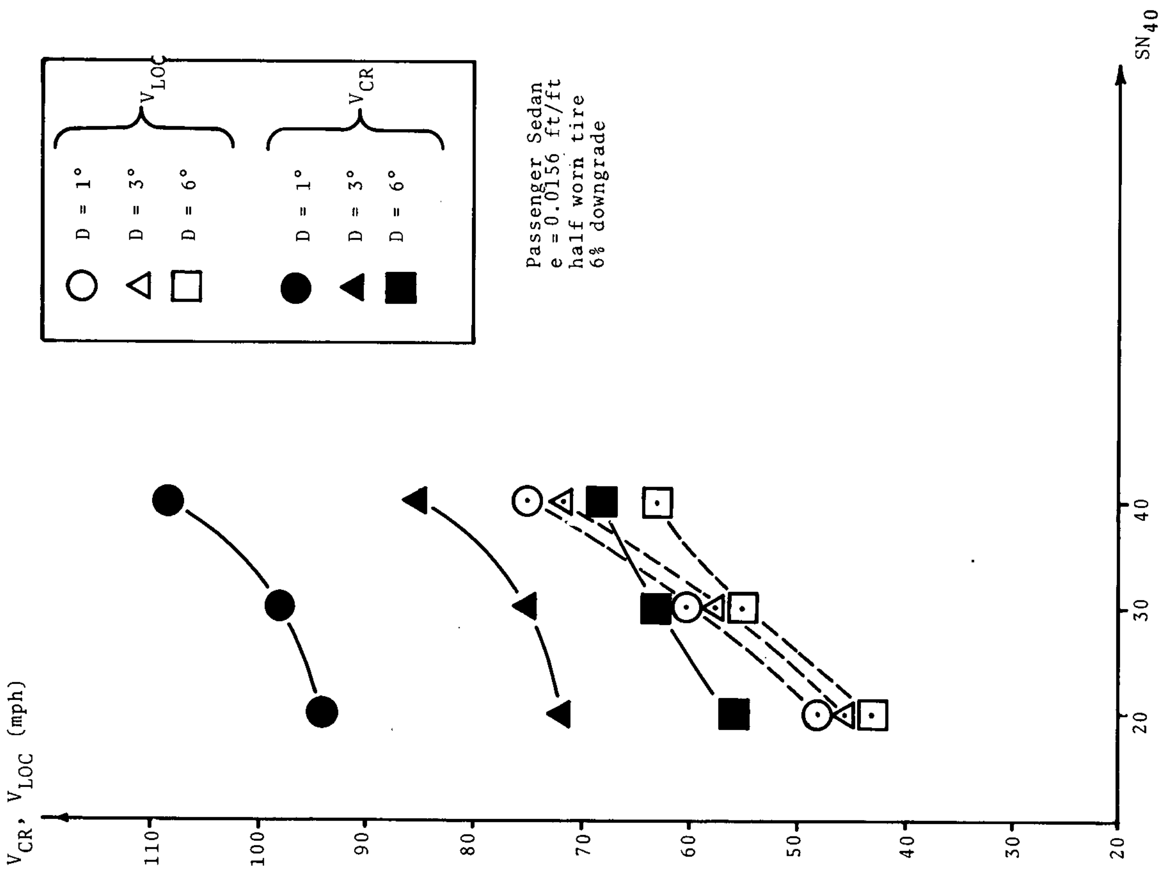


Figure 9. Curvature and SN_{40} *effects on* V_{CR}, V_{LOC}.

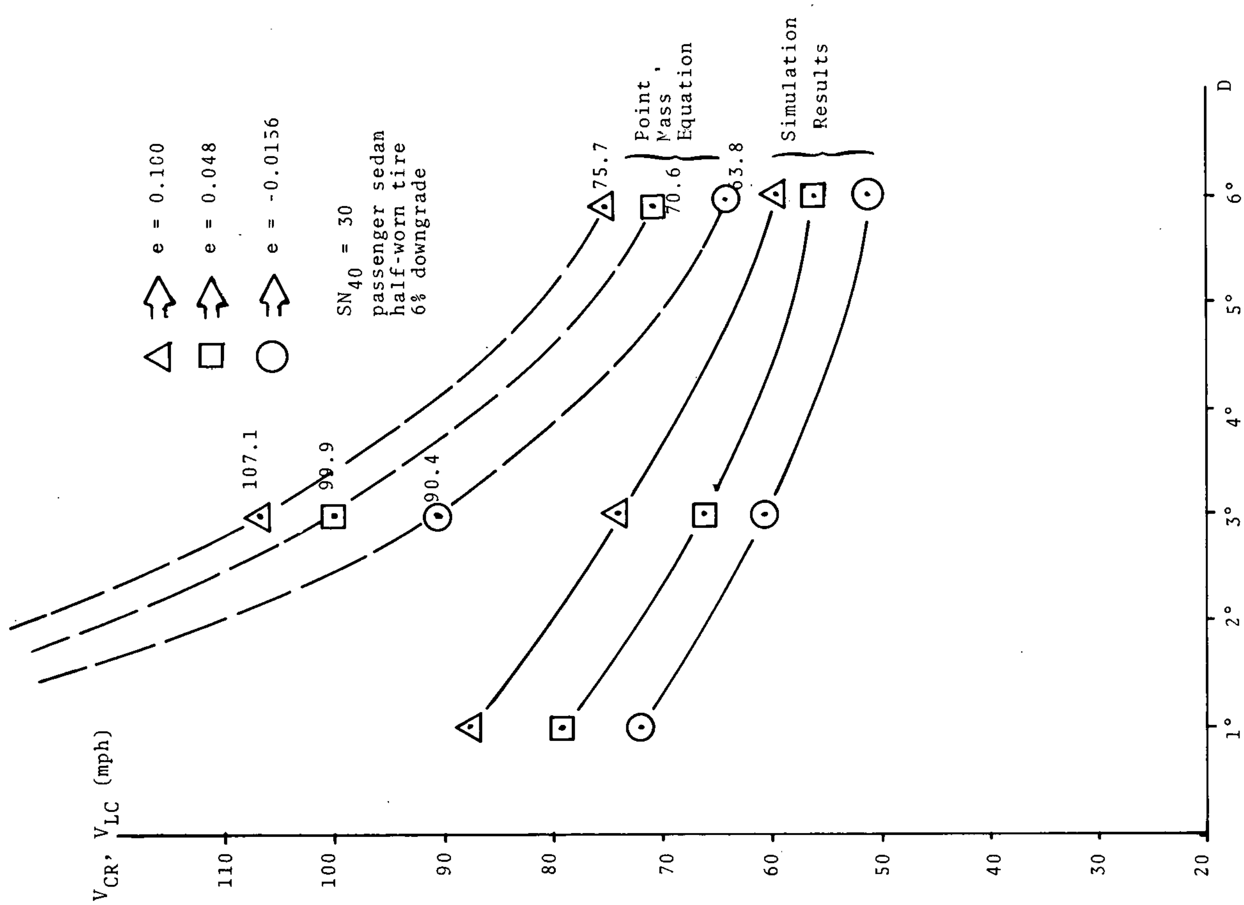


Figure 10. Effect of superelevation on V_{LC}.

predicting water depth, which can be written in the following form:

$$d = [(3.38 \times 10^{-3}) \left(\frac{1}{T}\right)^{-0.11} \left(\frac{L}{e^*}\right)^{.425} (I)^{0.59}] - T \qquad (3)$$

where:

$d =$ water depth above the top of the pavement texture, in.;
$T =$ average pavement texture depth, in.;
$L =$ pavement width, ft;
$e^* =$ pavement superelevation; and
$I =$ rainfall intensity, in./hr.

A similar expression developed at the Road Research Laboratory (*7*) can be written as follows:

$$d = (5.9 \times 10^{-3}) \left(\frac{LI}{e^*}\right)^{0.47} (e^{*2} + G^2)^{0.135} \qquad (4)$$

where G is the grade of the pavement and the other terms are defined as in Eq. 3.

Finally, Yeager and Miller at Goodyear (*8, 9*) have produced data that can be described by the equation

$$d = (9.6 \times 10^{-4}) \left(\frac{L}{e^*}\right)^{0.44} (e^{*2} + G^2)^{0.045} + (2.26 \times 10^{-3}) (I)^{0.49} (e^{*2} + G^2)^{0.19} \qquad (5)$$

where d is the total water depth including the average water depth in the surface texture.

In examining these three formulas for predicting water depth, it can be noted that Eq. 3 is independent of grade. The important roadway geometric factors in this expression are pavement width and superelevation. A weak dependence on texture depth is indicated. In Eqs. 4 and 5, the primary geometric factors are also pavement width and superelevation. A weak dependence on grade is indicated, and a texture term is missing. It can be concluded that road width and superelevation are the primary roadway factors affecting pavement surface drainage, with grade and texture depth being of secondary importance. Increasing the road width increases the run-off distance and thus leads to increased water depths. Increasing the superelevation increases the pavement slope and leads to lower water depths. Increasing the grade, on the other hand, increases both the slope and the run-off distance. Since the former leads to lower water depths and the latter to greater depths, the net effect is essentially zero. These conclusions are shown in Figure 11, which consists of a plot of water depth versus distance for separate sections of road having grades of 1 percent and 6 percent. Road width and superelevation are fixed at 24 ft and 0.0156 ft/ft, respectively. In comparing the three equations for predicting water depth, Figure 12 presents water depth versus road width as predicted by Eqs. 3, 4, and 5, for the following conditions: $I = 0.25$ in./hr, $e = (3/16)$ in./ft $= 0.0156$ ft/ft, and $T = 0.0117$ in. Much lower water depths are predicted by Eq. 3 than by Eqs. 4 or 5. Eq. 3 predicts negative water

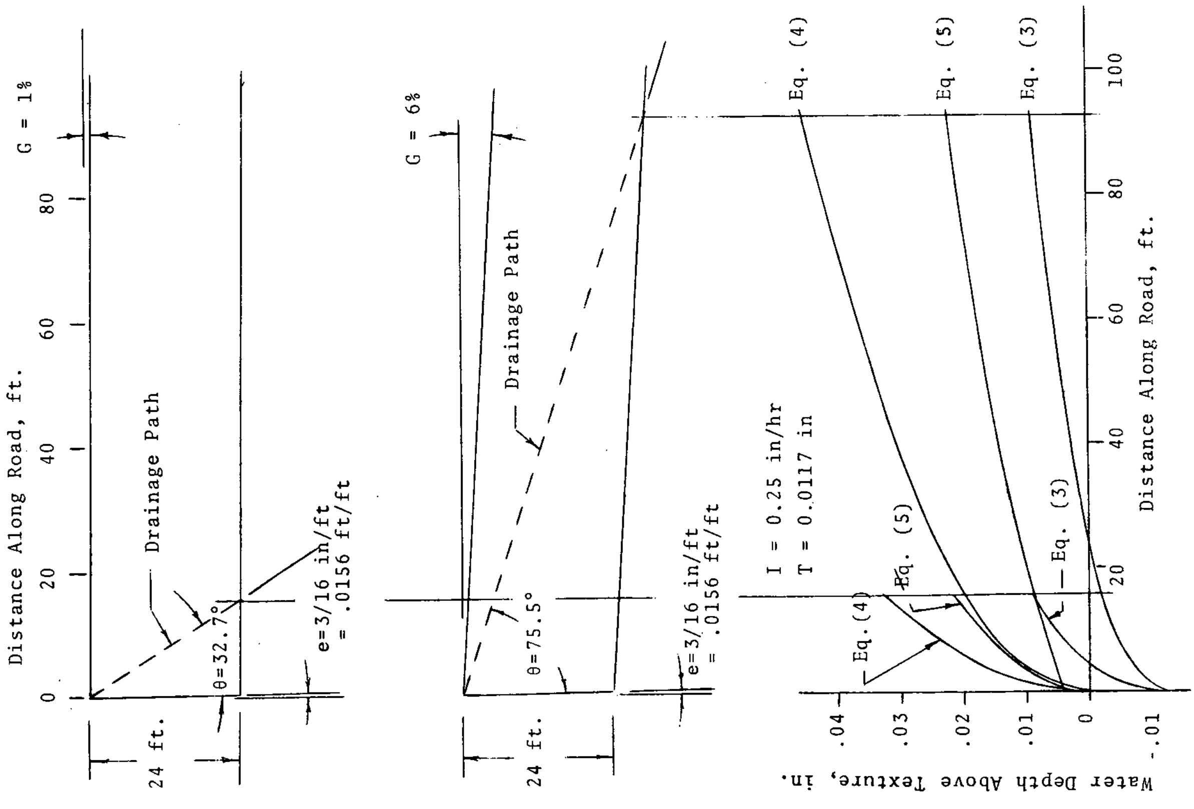


Figure 11. The influence of grade on water depth.

depths for small road widths (i.e., the water level is below the top of the pavement texture), whereas Eq. 4 predicts zero depth and Eq. 5 predicts a positive value. These differences result from differences in experimental techniques, definitions of water depth, and amount of data used by the three organizations. Also, the pavements used in the RRL research were comparatively more coarse-textured than those used at TTI and Goodyear. Because of these discrepancies and the importance of water depth on tire shear force potential, further research in the determination of water depth is recommended (see Chapter Four). In discussions in later sections of this report, water-depth predictions are based on Eq. 4.

A demonstration of the manner in which pavement drainage influences traction is given in Table 12. Three types of pavement sections are compared: a tangent, a long radius superelevated curve, and a long radius superelevated curve with outside shoulder sloped with and at the same rate as the roadway. For a rainfall rate of 0.25 in./hr, the traction available on the tangent is between 4 and 6 skid number units greater than that available on the curves. Also shown on Table 12 are the equivalent side force skid number units required to traverse each pavement section in a steady-state manner. (The term "equivalent side force skid number units" in this particular context refers to the rough equivalence of cornering force and braking force capabilities of most tires. It is recognized, of course, that the braking capability of a particular tire may be somewhat more, or less, than its cornering capability. The term is used imprecisely here in a comparative sense rather than as an absolute measure.) Adding the losses due to both water depth and steady-state driving requirements yields the result that traction available on the curve sections is 10 to 12 SN units less than that available on tangents. Thus, for the conditions indicated, pavement skid resistance on a curve should be greater by 10 to 12 skid number units if a vehicle is to travel a curve with the same margin of safety during wet weather as exists on a tangent.

In summary, pavement water depth for a given precipitation rate and for normal ranges of grades and curvature is primarily a function of pavement drainage width and superelevation. (This may not apply to special geometric sections such as interchange ramps roadways and transitions from tangents to curves.) Grade and pavement texture are secondary factors. The margin of wet-weather friction available for emergencies is less on curves than on tangents. This margin is reduced by the friction requirements needed for steady-state cornering as well as by the increased water depths that exist on curves as a result of the longer drainage path lengths that prevail on curved sections.

SELECTION AND EVALUATION OF PROBLEM SITES

Two highway sites were selected and subjected to an indepth evaluation to determine accident causation factors. One site is at a curve located on the westbound portion of the Ohio Turnpike between mileposts 166.4 and 166.6 (just south of Cleveland). The other is at a curve on I-95 near Fredericksburg, Va., where there is an interchange between I-95 and US 1. These two sites were chosen from an initial group of six, with five of the original six being subjected to a preliminary on-site evaluation. Each of the six sites is characterized by an alignment geometry combining vertical grade with horizontal curvature. In each

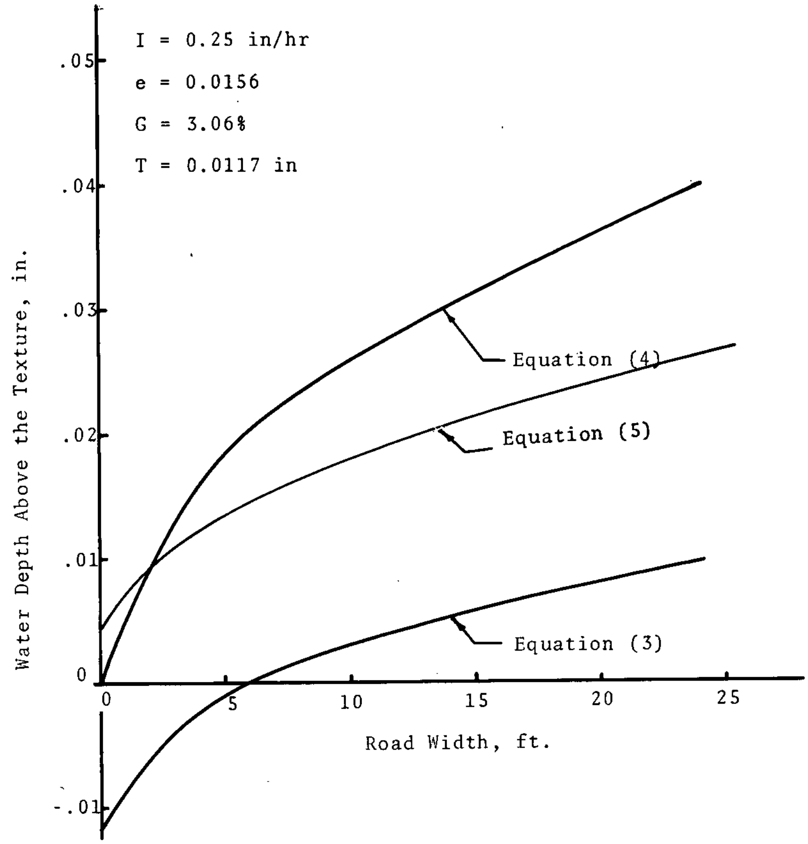


Figure 12. A comparison of water-depth prediction equations.

case, the curvature and grade are relatively gentle and well within the limitations suggested by the AASHTO (*2*). The manner of selecting the six initial sites, a description of each site, and the methods used in the preliminary on-site evaluations are discussed in Appendix D of Part II. A complete discussion of the indepth evaluation of each of the two selected sites is also given in Appendix D. A summary of these indepth evaluations is presented in the next section, along with an analytic example in which simulated maneuvers are compared with available accident data.

Evaluation of the Ohio Turnpike Site

The Ohio Turnpike site is a gentle 1° curve located between Exits 10 and 11. The site lies at a point where the roadway is on a 60-ft fill, with the grade varying between 2 percent and 3 percent downward. No interchange or service plaza is within 3 mi of the site, and there are no signs near the site.

From January 1, 1966 to June 30, 1970, the number of recorded accidents between mileposts 166.4 and 166.6 was the highest for any 0.2-mi segment on the Turnpike. From January 1, 1966 to May 1, 1973, a total of 55 accidents on the 0.2-mi segment was recorded. Of the total, 37 (or 67 percent) involved "skidding" or "loss of control" on a wet surface. Although data are not always recorded, 16 of the involved vehicles were shown on the accident reports to have had smooth tires.

Rainfall data recorded at nearby Cleveland Hopkins Airport show that during the hour of the accident the rainfall accumulation was less than 0.1 in. almost 70 percent of the time. Instantaneous rainfall rates may have varied from this at the site.

Prior to June of 1970 the pavement at the site was portland cement concrete. Although the skid number was never directly recorded, measurements for similar sites along the Turnpike would suggest a skid number range of between 25 and 35 at the site during this period. The site was resurfaced with a bituminous overlay during June of 1970. Recent skid trailer measurements indicate that the pavement SN_{40} values at the site are between 40 and 50.

Prior to resurfacing, 79 percent of the accidents at the site occurred during wet weather. After resurfacing, this number decreased to 62 percent. These percentages are both much higher than the percentages that occur along the Turnpike and, as such, indicate a definite overinvolvement of wet-weather accidents.

The major cause of accidents at the site is apparently the result of inadequate pavement drainage. As was indicated earlier, the water depth on a uniform pavement surface during rainy weather is primarily determined by road width, superelevation, and rainfall intensity. At the subject site, the effective road width for drainage consideration is 34 ft. This width includes the 24-ft width of the two traffic lanes plus a 10-ft paved shoulder, all of which are superelevated at the same rate of 0.0156 ft/ft. On the crowned tangent sections of the Turnpike, the drainage width is only 12 ft, with the cross slope also being 0.0156 ft/ft. The net result of the greater drainage width on the curved section located at the subject site is that water

TABLE 12

A COMPARISON OF WET-WEATHER TRACTION PROPERTIES FOR TANGENT AND CURVE PAVEMENT SECTIONS UNDER STEADY-STATE DRIVING CONDITIONS

Pavement Section[1]	Drainage Width ft.	Computed Maximum Water Depth for 0.25 in/hr Rainfall Rate, in.[2]	Traction Loss Due to Water Depth SN Units[3]	Equivalent Side Force SN Units Required for Steady-State Travel of Section[4]	Total Traction Loss	Traction Loss Compared to Tangent
Tangent	12	.028	3	0	3	0
Superelevated Curve, Shoulder Not Superelevated	24	.040	7	6	13	10
Superelevated Curve, Superelevated Shoulder	34	.046	9	6	15	12

1. Crown slope and superelevation cross slope rate at 0.0156 ft/ft in all cases.
2. Based on Equation (4).
3. Full tread 5.20 x 10 cross-ply tire at 80 mph where losses are compared with a water depth of 0.02 in. (0.02 in. is the water depth used in the standard ASTM pavement skid test procedure).
4. 80 mph speed, 1° curve.

depths during wet weather are roughly twice those occurring on tangent sections.

An analysis of the accident data and the pavement drainage analysis discussed previously indicate that the major problem at the Ohio Turnpike site is inadequate traction during wet weather caused by inadequate cross slope for pavement drainage. Possible methods for improving situations of this type are:

1. Establish and enforce tire tread depth requirements.
2. Establish and enforce reduced wet-weather speed limits at problem sites.
3. Improve the pavement drainage.
4. Increase the pavement skid resistance.

Pavement drainage can be improved by decreasing the drainage length, by increasing superelevation with a pavement overlay, and/or by providing drainage paths below the tire/road contact surface. An increase in superelevation at the site from 0.0156 to 0.06 will reduce water depths by about one-third—a reduction that would not appear to be a complete solution. Increasing superelevation beyond 0.06 is somewhat impractical and does not produce a significant reduction in water depth. Water can be made to drain below the tire/road contact surface by adding a wearing course of large, sharp, aggregate—such as an open graded, asphalt friction course—or by grooving the pavement in a transverse direction. The best suggestion seems to be to increase the surface superelevation to 0.06 by adding an open-graded friction course. The superelevation increase will improve drainage, whereas the wearing course will improve both the drainage and the surface skid resistance.

Evaluation of the I-95 Site

The selected site, on southbound I-95 near Fredericksburg, Va., consists of a curve of 1°00′56″ combined with a downgrade that varies between 2.6 percent and 3.1 percent. The site is located at an interchange with US 1, with I-95 passing over US 1 on a bridge midway between the exit and entrance ramps to and from US 1.

From December 18, 1964 to June 26, 1972, 133 accidents were recorded on southbound I-95 in a region extending 1,000 ft beyond the beginning and ending of the exit and entrance speed-change lanes. Of this number, 45 accidents (or 34 percent) involved skidding or loss of control on a wet surface. Seven percent of the total were classed as sideswipes, 26 percent as rear-end collisions, and 59 percent involved a collision with a fixed object along the roadside. Worn tires were reported as involved in only 7 percent of the accidents, although tire condition was not always noted on the accident report.

The regions between the exit ramp and the bridge (approximately 1,000 ft) and between the bridge and entrance ramp (also about 1,000 ft) had approximately equal percentages of involvements (27 percent and 24 percent, respectively). The same is true of the 1000-ft segments before the exit ramp (17 percent) and after the entrance ramp (15 percent). Seventeen percent of the accidents occurred at the bridge. A general review of the collision diagrams for the site (*10*) suggests that a majority of the accidents occurred as a result of indecision in weaving, merging, exiting, and entering situations.

Rainfall data recorded at nearby Quantico Marine Base show that during the hour of the accident the rainfall accumulation was less than 0.1 in. in 39 of the 51 wet-

weather accidents. Instantaneous rainfall rates varied from this at the site.

The pavement at the site is portland cement concrete. The entire length of the site was longitudinally grooved during June 1972. However, no statistically significant improvement in wet-weather skidding accident statistics has been noted at the time of this investigation. Recent skid measurements made at the site indicate that the SN_{40} value is 53 to 55 parallel to the grooves in the travel (right) lane and 60 to 62 in the passing lane.

Accident causation factors at the subject site are apparently the result of many factors acting both separately and in concert. These factors include reduced pavement traction due to inadequate water drainage, short speed-change lanes, insufficient sight distance, and obstructed signs.

The superelevation rate on the I-95 curve is the same (0.0156 ft/ft) as that on the Ohio Turnpike site, but the drainage width is less (24 ft for I-95 as compared with 34 ft on the Ohio Turnpike). The smaller road width is caused by the fact that the shoulders on the high side of the I-95 curve slope away from the roadway. Consequently, the computed water depth during a rainfall of 0.25 in./hr is 0.040 in. on I-95 as opposed to 0.046 in. in Ohio.

Site geometry and signing often combine to produce situations in which drivers are given to indecision. For example, just ahead of the exit ramp at the subject site, a vertical crest curve tends to hide the exit deceleration lane from oncoming drivers. An exit sign indicating that the exit is for US 1 and the city of Massaponax is completely obscured by two other signs. An exit speed advisory sign of 25 mph can not be seen until the vehicle actually turns into the exit. The exit ramp is relatively steep (6.5 percent downgrade) and contains a reverse curve, initially 4.9° to the right and then 7.9° to the left. Considering that the exit ramp advisory speed is 25 mph, the exit deceleration lane, although longer than would be suggested by current AASHTO recommendations for the existing ramp curvature, is at least 150 ft too short for a 25-mph ramp speed.

Proceeding south past the exit ramp, a high embankment and vegetation on the inside of the curve hide the bridge from oncoming motorists. As the motorist approaches the bridge, the bridge railings, being relatively high and within 3 ft of the road edge, also contribute to the loss of sight distance. Because the bridge is both on a curve and at the top of a crest (the road grade changes from −2.64 percent to −3.1 percent just south of the bridge), the road ahead can not be seen until the driver is on top of the bridge deck. Thus, there is a continuing sight distance problem in the region located between the exit ramp and the south end of the bridge deck.

In the region located between the exit and the bridge, there is also a variable-message sign that is used to warn motorists of an icy bridge deck. This sign is hidden from oncoming motorists, by a no-hitchhiking sign, until the motorist is almost on the bridge.

South of the bridge, the entrance ramp and acceleration lane are difficult to see because of the road crest previously mentioned, the roadside vegetation, and the fact that the ramp merges on the inside of the curve and is thus hidden by road curvature. Further, the entrance ramp is a sharp curve (8.1°) on a steep upgrade (3.4 percent) with little sight distance. Many motorists using the ramp have been observed to enter the acceleration lane at no more than 20 mph. Considering these facts as well as the additional fact that the freeway enters an upgrade of almost 3 percent along the length of the acceleration lane, the existing acceleration lane is almost 1,800 ft shorter than the minimum length recommended by AASHTO.

Suggested ways of improving the site include:

1. Enforcing a reduced speed limit at the site.
2. Improving the drainage of the pavement.
3. Improving the friction level of the pavement.
4. Improving signing.
5. Improving the sight distance.
6. Improving the interchange ramps.

Methods for implementing items 1 through 3 have already been discussed with respect to the Ohio Turnpike site and need no further discussion here.

Suggested ways of improving signing at the site include (1) removing or relocating the signs obscuring the exit sign—US 1, Massaponax; (2) relocating the advisory exit speed sign, so that it can be seen from the deceleration lane; (3) removing or relocating the no-hitchhiking sign obscuring the icy bridge warning sign; and (4) adding a MERGE message below the merge arrow just prior to the entrance lane.

The sight distance at the site can be improved by cutting away, or removing, obstructions on the inside of the curve. Suggested measures include (1) removing part of the earthen embankment prior to the exit and between the exit and the bridge; (2) removing excess vegetation all along the interchange roadside; (3) widening the bridge deck so that a minimum of 10 ft of shoulder width is available; (4) faithfully mowing the grass in advance of both the exit and entrance ramps; (5) adding raised curbs, which are painted for high visibility, on the far side of each ramp; and (6) making the pavement in the speed change lanes to contrast with the freeway pavement.

Finally, it is suggested that both speed change lanes at the interchange ramps be lengthened. The exit ramp deceleration lane should be at least 800 ft long and the entrance ramp acceleration lane about 2300 ft long.

Simulation of an Accident Scenario

One very common situation mentioned in the reports of accidents occurring on the Ohio Turnpike in the vicinity of milepost 166 was that of loss of vehicle control because of rear-end sliding or "fishtailing" while cornering. Defective or nearly smooth tires were frequently observed to exist in these cases. It should be noted that the operating speeds mentioned in the accident reports ranged from about 40 mph to 65 mph. These findings suggested that simulation be employed to examine the consequences of this particular accident scenario. The details of the site and assumed operating conditions are given as follows:

Curvature = 1°
Downgrade = 2 percent
Superelevation = 0.0156 ft/ft

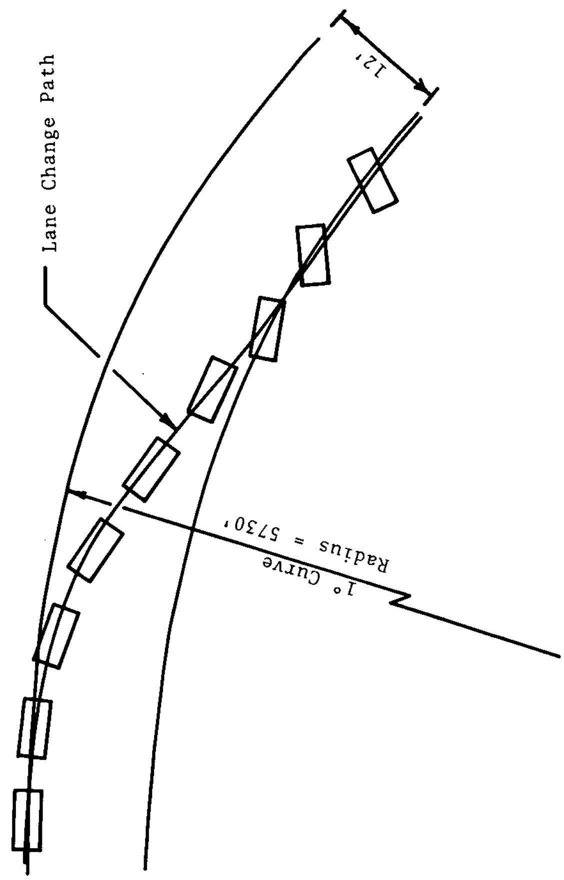


Figure 13. Accident scenario simulation result.

Rain
Half-worn tires on front (half-worn tires assumed to be 85 percent as effective as ASTM standard skid test tire)
Fully-worn tires on rear (fully worn tires with approximately 3/32-in. tread assumed to be 60 percent as effective as ASTM standard skid test tire)
Vehicle = 1966 Ford Custom
Surface Skid Number (SN_{40}) = 30
Surface Skid Number Gradient = (—0.5) mph^{-1}

Two different maneuvers were simulated. The first was a simple cornering maneuver (with drive thrust maintained) run at 75 mph. The second was a 65-mph cornering maneuver with the addition of a 12-ft lane change. The 75-mph cornering maneuver was performed with no difficulty. However, the cornering and lane-change maneuver at 65 mph was unsuccessful. The vehicle began to make the lane change to the inside, but the rear-end spun out during the correction phase, as shown in Figure 13. The simulation results indicate that this maneuver can be accomplished successfully by the assumed tire/vehicle system operating under the specified roadway conditions only at speeds of 50 mph or less.

DESIGN POLICY ANALYSIS

The formula used in the AASHTO geometric design publications for curve design is:

$$e + f = \frac{V^2}{15R} \qquad (6)$$

where:

e = roadway superelevation, ft/ft;
f = side-force factor, dimensionless;
V = vehicle speed, mph; and
R = radius of curve, ft.

In its present form, the formula indicates that the centrifugal force produced by turning is balanced by the force of gravity developed by superelevation, e, plus the tire/road interface forces, f. To derive this formula the vehicle is treated as a point mass and highway grade is neglected.

In using the formula, values of f are selected primarily to reflect driver comfort, because f represents the value of lateral acceleration (not accommodated by superelevation) that the driver feels. These comfort considerations limit f to values that are apparently well below the condition of imminent skidding for commonly existing tires and pavement conditions. Values of e are then computed from the formula for given values of R and V (V is considered to be the highway design speed). Values of e are limited to about 0.12 in regions where snow and ice do not exist, and to about 0.06 to 0.08 in regions where snow and ice conditions are prevalent. In cases where the value of e, as computed from the formula, is greater than the practical limit, the design of the roadway is usually changed to increase the radius of curvature.

Development of Margin of Safety

In the following material, the curve design formula is examined for its applicability to situations involving a combined horizontal curvature and vertical grade. Next, the over-all philosophy of alignment design is discussed in terms of (1) the actual cornering characteristics of a real automobile (not a point mass); (2) additional constraints imposed by emergency maneuver requirements; and (3), in consideration of (1) and (2), the roadway skid-resistance requirements stemming from the tire/road interaction mechanism.

The Curve Design Formula in the Presence of Combined Horizontal Curvature and Vertical Grade

On retaining the assumption that the vehicle is a point mass and on including the influence of gravitational forces deriving from grade, the curve design formula can be written as:

$$f + \sin e^* \cos G = \frac{V^2}{gR} \cos e^* \qquad (7)$$

where the terms are defined as before, and e^* is the apparent superelevation. (See Appendix E in Part II for a thorough discussion and derivation of Eq. 7.) Note that in constructing a curve on a grade, the superelevation built into the road is the "apparent superelevation."

The difference between Eq. 6 and Eq. 7, or the error resulting from the use of the AASHTO formula in place of the exact equation, is primarily a function of superelevation rate—the greater the superelevation, the greater the error. For superelevation values as large as 0.12, however, the error is only 0.73 percent. Thus, within the range of

values of V, R, e, and G commonly encountered, the AASHTO curve design formula is virtually equivalent to the exact formula and is essentially independent of grade. The formula, as presently applied, is equally applicable to the design of horizontal curves alone, as well as to curves constructed on upgrade and downgrade vertical alignments.

Margin of Safety for Curve/Grade Sites

On a downgrade, a component of gravitational acceleration, which is equal to the grade, G (for small grades), must be overcome to bring the vehicle to a stop.

On a curve, the simple point mass equation of equilibrium states that

$$\bar{f} = \frac{V^2}{Rg} - e \tag{8}$$

where the terms are as defined before and:

$\bar{f}$ = the acceleration (in g units) that must be provided to maintain the path ($\bar{f}$ is not to be confused with the f term of Eq. 6, the AASHTO design formula; the latter term denotes a cornering comfort condition); and

V = the velocity (which may be taken equal to a desired or selected speed).

For a vehicle traveling at the speed limit, V_{SL}, on a path of radius R with superelevation e, the quantity $\bar{f}$ represents a first-order approximation to that portion of the total acceleration capability required to keep the vehicle on the path. Therefore, $\bar{f}$ represents an estimate of the acceleration capability (in g's) that is not available for maneuvering on curves. Consequently, $\bar{f}$ and G are first-order estimates of the loss in available acceleration capability due to curvature and grade, respectively.

Combined Influence of Curve and Grade

An examination of the horizontal alignment design formula (as discussed in the previous section) indicates that grade has negligible influence on the design formula per se. However, conditions may exist at curve/grade sites under which tire and vehicle properties limit the acceleration capability available for stable vehicle operation. The side force that can be generated by a pneumatic tire is reduced when high levels of longitudinal (braking- or traction-induced) slip are present. Thus, since increased braking force or propulsive force is needed on downgrades or upgrades, respectively, the side force available for maneuvering could be reduced from the level of side force available on a level section of road. Also, the increased braking required on a downgrade causes more load transfer from the rear tires onto the front tires. This increases the possibility of rear-wheel lock-up. If the brake proportioning of the vehicle allows the rear wheels to lock while the front wheels are still rolling, the vehicle becomes directionally unstable and can "spin" when some directional disturbance is encountered or produced by the driver.

On a divided highway it seems reasonable to hypothesize that a driver seldom uses his forward acceleration capability to avoid a crash. However, braking is frequently necessary to avoid a collision. The driver can usually reduce his forward acceleration if he is encountering stability problems; but, in a braking situation, the driver may have little choice except to try to stop. Thus, downgrades are likely to present more dangerous situations than upgrades, because more brake force is required on a downgrade than on an upgrade to obtain the same level of deceleration.

Simulated Maneuvers at Curve/Grade Sites

In the simulation study, calculations were made to compare vehicle performance in a steady turn with performance in emergency maneuvers. The two emergency maneuvers selected for comparison were a lane change and a lane change combined with an abrupt stop. The maximum velocity for successfully performing each maneuver was determined from the simulation results. These velocities were termed V_{CR}, V_{LC}, and V_{LOC}, as defined earlier. The simulation results are presented in terms of these velocities in the second part of Appendix B, and were discussed earlier (under "Simulation Findings"). The question being addressed here is: What bearing do the simulation results have on highway design policy for curve/grade sites?

The AASHTO design policy for horizontal curves is based on the point mass equation for an equilibrium turn. In this policy the road surface is required to supply to the vehicle an amount of lateral force that is bounded by occupant comfort. Under ordinary circumstances, including normal rainstorms, the frictional potential of the roadway is usually more than adequate to supply this amount of lateral force at reasonable operating speeds. The simulation results indicate that, for speeds less than 70 mph and curves less than 3° with reasonable superelevation, V_{CR} will not be reached even by vehicles operating with poor tires on relatively low-friction surfaces. (Even for 6° curves, in worst-case situations, V_{CR} is 56 mph.) Thus the design policy seems to be adequate for assuring satisfactory vehicle operation in making "normal" turns. Furthermore, it appears that the design policy provides a reasonable guide for laying out highway geometrics.

The Need for a Margin of Safety

To reduce skidding or loss of control accidents, it appears that a margin of safety is needed to allow for maneuvering at curve/grade sites. Clearly, the computer results for V_{LC} and V_{LOC} indicate that these velocities are much less than V_{CR}. Thus, roadway and operating conditions imposing a requirement for maneuvers constitute important factors that should be considered in road design.

The maximum speed, V_{LC}, for a lane change is highly dependent on the degree of curvature and superelevation, much in the same manner as V_{CR} depends on curvature and superelevation. The simulation results indicate that there are cases where a driver with half-worn tires operating on an $SN_{40} = 30$ surface will have trouble trying to make an abrupt lane change at 70 mph on a 3° curve.

When braking is added to the lane-change maneuver, the computer results indicate that vehicle control problems will arise at speeds less than 60 mph on surfaces with $SN_{40} = 30$. This result is not highly dependent on grade,

curvature, or superelevation over the ranges of these variables used in the simulation.

These findings show that the margin of safety needed for maneuvering can not be achieved exclusively by means of geometric design. The road surface must provide a friction margin if a margin of safety is to be provided to reduce accidents at curve/grade sites. Nevertheless, superelevation levels can be selected at the upper end of the AASHTO-recommended values (1) to provide as much of a safety margin for turning maneuvers as possible and (2) to maintain the friction potential of the road during rainstorms by increasing the surface drainage.

Value of the Margin of Safety for Emergency Maneuvers

Given that roads are designed in accordance with the AASHTO policy, the question arises as to how the margin of safety for abrupt and emergency maneuvers is to be determined. In this project, the answer to this question was sought by simulating the tire-vehicle-roadway-driver system. This methodology posed several difficult questions such as:

1. Which tire, surface, and vehicle are to be used?
2. Since the tire/road forces are highly dependent on velocity, how does one compare results for V_{LOC} with results for V_{CR} (for example, $V_{LOC} = 57$ mph and $V_{CR} = 77$ mph for a baseline case in the simulation study)?
3. Are there more maneuvers worth considering? (Certainly there are many possible variations in the timing and level of braking, and possibly these variations could be such that both grade and curvature might be important.)

These questions indicate limitations and reservations with respect to the generality of the simulation findings. (Exercising the simulation is analogous to running vehicle tests; consequently, these same problems would exist if vehicle testing were to be used to determine an adequate margin of safety.) Nevertheless, the simulation results do provide a basis for tentative estimates of the pavement surface skid resistance needed to allow controllable maneuvering. For example, it appears that a minimum skid number for executing a lane change and stop maneuver without loss of control can be estimated from the computer results. These computer simulation results indicate that $SN_{40} = 40$ is the minimum pavement skid number needed to ensure that V_{LOC} is greater than 70 mph on 3° curves for ordinary passenger vehicles with reasonably good tires traveling on wet pavements. A value of SN_{40} greater than 40 is required to produce a factor of safety that is adequate for tires worn to the legal limit.

As stated earlier, the findings obtained with respect to V_{LC} are significantly dependent on highway geometrics. These findings are derived from a mathematically complex set of nonlinear differential equations in which the shear-force characteristics of all four tires are computed using complicated empirical relationships. Nevertheless, an examination of the computer results indicates that V_{LC} can be approximated by a simple linear function of the degree-of-curvature, D, superelevation, e, skid number, SN, and tire factor, T_F, for practical values of these variables as exist in curves ranging from 1° to 4° of curvature. Consequently, this linear function can be used to obtain the following approximate expression for predicting the skid number required for safe execution of a lane-change maneuver on a curve:

$$\overline{SN}_{40} = \frac{V_{LC} + 6.5D - 154e - 37T_F - 7.7}{1.3} \tag{9}$$

where the terms are as defined before and:

$\overline{SN}_{40}$ = the minimum pavement skid number measured at 40 mph with a skid trailer in conformance with ASTM Method E-274;
D = the degree of curvature; and
T_F = a gross factor relating tires in use to the ASTM skid trailer reference tire.

Eq. 9 is a very simple formula representing a host of complex factors. Values for tire factors, T_F, were assumed as 1.2 for new tires, 0.85 for half-worn tires, and 0.6 for fully worn tires. The speed gradient pavement skid resistance assumed in deriving this formula is —0.5 SN per mph. Also, water depth is not treated directly in this formula. Because the ASTM SN_{40} values are obtained at a water depth of approximately 0.02 in., this equation may be applicable to weather conditions resulting in about 0.02 in. of water on the road. If heavy rains or poor drainage conditions exist, the influence of water depth must be considered in determining the tire/road force potential. Nevertheless, this formula is useful for (1) estimating the pavement skid resistance needed for a desired V_{LC} for a given set of roadway geometrics with a specified state of tire wear, or (2) predicting V_{LC} for a given set of roadway and tire conditions.

Besides being useful for estimating a value of skid number, these lane-change results can also be used to derive a skid number margin. The acceleration needed for the steady turn portion of a lane change on a curve is nearly constant, because the radius of the turn is only changing about 9 to 12 ft during the lane change for typical highway curves with radii of 1,000 to 6,000 ft. Consequently, the maximum lateral acceleration used in a lane change can be approximated by the following expression:

$$a_L = a_{LC} + \frac{V_{LC}^2}{Rg} - e \tag{10}$$

where the terms are as defined previously and a_{LC} is approximately equal to the lateral acceleration (in g's) used in a lane-change maneuver on an equivalent tangent section of the road.

Note that the term, V_{LC}^2/Rg, represents the loss in available acceleration capability due to the constant velocity turn. This quantity minus e is equal to the factor $\overline{f}$, discussed at the beginning of this section. Thus $\overline{f}$ evaluated at V_{LC} represents an estimate of the acceleration margin needed to compensate for the curved path. An extra margin of maneuvering safety could be built into curved sections of the roadway by appropriately increasing the skid number on these sections over the skid number on tangent sections. It is reasonable to consider increasing the skid number on a curve by an amount determined by $\overline{f}$; that is,

$$SN_C = SN_T = 100\,\overline{f} \tag{11}$$

where SN_C equals the improved skid number on the curve at the velocity V_{LC}, and SN_T equals the desired minimum skid number on the tangents of the road at V_{LC}.

The accident analysis shows that grade and curvature do not interact to produce a statistically significant increase in accidents at curve/grade sites over and above the accident rate predicted from curvature and grade individually. The error analysis and computer simulation findings confirm this conclusion. Also, upgrades do not seem to be important factors in accidents on the Ohio or Pennsylvania Turnpikes. Consequently, it seems reasonable to allow an independent skid number safety margin for downgrade sites; namely,

$$SN_G = SN_T + 100G' \tag{12}$$

where:

SN_G = the safety margin skid number for grade sites at a velocity V which is at or near the speed limit;
SN_T = a desired minimum skid number for level tangent sections of the road at the selected velocity, V; and
G' = the magnitude of the downgrade, percent.

Furthermore, at curve/grade sites, the effects of grade and curvature can be combined additively to obtain the following expression for a safety margin skid number:

$$SN_{CG} = SN_T + 100(\bar{f} + G'') \tag{13}$$

where the terms are as defined before and:

SN_{CG} = the safety margin skid number for curve/grade sites at a velocity, V, which is at or above the speed limit; and
G'' = the magnitude of the grade in percent for downgrades and zero for upgrades.

As pointed out in sections of this report dealing with pavement-drainage analysis and evaluation of the Ohio Turnpike site, the margin of wet-weather friction available for emergencies is less on curves than on tangents. For example, it is estimated that an additional skid number margin of four to six is needed at sites similar to the Ohio Turnpike site to compensate for the additional water depth on the curve at that site.

The findings of the accident data analysis show that the 1° curves on the Ohio Turnpike are the most likely places for loss-of-control accidents. When first obtained, this result was surprising, in that higher values of centrifugal force are developed on sharper curves and, thus, greater friction potential is needed from the road. However, a small superelevation (0.0156 ft/ft) was used at the Ohio Turnpike 1° curve site. Consequently, the acceleration, $\bar{f}$, which must be provided by the tire/road interface, is relatively large. Moreover, since the superelevation is low on the 1° curves, the water depth on the 1° curves will be greater than on smaller radius curves having a larger superelevation. Consequently, it is possible that on the Ohio Turnpike the most slippery condition encountered by vehicles with worn tires traveling in a heavy rainstorm occurs on the 1° curves. Thus, for long-radius curves, higher superelevations are required to compensate for the increased drainage path length in order to develop the skid number margin needed to reduce the likelihood of loss of control in wet-weather conditions.

CHAPTER THREE

INTERPRETATION AND APPLICATION OF FINDINGS

The findings of the study do not indicate that the AASHTO design formula for horizontal curves should be modified for application to highway sections with combined horizontal curvature and vertical grade. The AASHTO formula provides a practical method for arriving at reasonable geometric designs for curve sites when the selected values of superelevation are large enough to furnish adequate drainage. The findings developed in the turnpike accident study and in the field site studies do show, however, that some sites possessing combined grade and curvature do have an extraordinary number of accidents. In addition to showing the drainage deficiencies that derive from curve geometry, the analytical and simulation studies indicate that vehicle maneuvering at curve/grade sites develop larger lateral acceleration values than at comparable tangent sections. Accordingly, the findings of the program are interpreted in this chapter to recommend tentative guidelines for (1) reviewing the design practices for new sections of highway and (2) evaluating accident-causation factors at existing high-accident-rate sites.

NEW DESIGN APPLICATIONS

The major applications of the project findings to the geometric design of new roadways are as follows:

1. The AASHTO design guidelines for superelevation rate should be followed but increased emphasis should be placed on adequate pavement surface drainage, particularly on long-radius curves and other locations where the drainage length is longer than one lane width.

2. Pavement surface skid resistance should be larger than the desired minimum for tangent sections on those sections of highway, such as downgrade curve sites, where operating conditions impose a greater demand for tractive forces at the tire/road interface.

TABLE 13

COMPARISON OF SUPERELEVATION RATE POLICIES FOR A ONE-DEGREE CURVE

Organization	Superelevation Rate - ft/ft
Ohio Turnpike Commission	.0156
Pennsylvania Turnpike Commission	.0139
Michigan Department of State Highways and Transportation	.04
Pennsylvania Department of Transportation	.0208 - .0260
Virginia Department of Highways	.0156
AASHTO:	
70 mph Design Speed*	.033 - .043
80 mph Design Speed*	.041 - .048

*The lower value is for e_{max} = 0.06, while the upper value is for e_{max} = 0.12.

3. Geometric design and signing practices should be carefully reviewed to ensure that these practices, in and of themselves, do not promote additional maneuvering and thereby lead to an increased potential for loss of control.

The application of these findings to design practice is outlined in the following discussion.

AASHTO Cross-Section Design Policy

The six sections of highway investigated in this program were designed by five different highway organizations. None of these sections were designed using the superelevation rate levels recommended in the AASHTO geometric design publications. The primary area of difference lies in the range of long-radius curves. Recommended superelevation policies for five highway organizations for a 1° curve are given in Table 13. Only one of these superelevation rates —that for the Michigan Department of Highways and Transportation—is reasonably close to that recommended by the AASHTO. Even in this case, the level used has just been recently adopted, and many 1° curves on Michigan freeways are superelevated at no more than the crown slope, with the reverse crown having been removed. In most cases, the superelevation used is a factor of two or three below the recommended AASHTO level. Although Table 13 shows comparisons for only five organizations, lack of conformance with AASHTO recommendations for superelevation rate appears to be the rule rather than the exception.

The current AASHTO policies regarding pavement surface drainage considerations in cross-section design are contained in Chapters 3 and 4 of Ref. (*2*) and in Chapters H and I of Ref. (*3*). On page 162 of the GDRD (*2*), the policy regarding drainage for the sharpest curve without (i.e., not requiring) superelevation is stated as follows:

> The minimum rate of cross slope applicable to traveled ways is determined by drainage requirements. Consistent with the type of highway, amount of rainfall, snow, and ice, the values usually accepted range from 0.008 foot per foot for high type rigid surfaces to approximately 0.02 for low type flexible surfaces; see Normal Cross Slope, chapter IV. Here these values are the extreme. In more general use are the values from 0.01 to 0.015. A value of 0.012 is about average and, for discussion purposes, is used herein as a single intermediate value representative of the general range for uncurbed pavements. Steeper cross slopes are needed on curbed pavements to minimize the spread of surface water flow.

Similarly, on page 359, the policy regarding drainage for superelevation for curves at intersections is stated as:

> The rate (i.e., superelevation rate) of 0.02 is considered a practical minimum for effective drainage across the surface.

On pages 349 through 351 of DUHAS (*3*), the policy for drainage in terms of cross slope arrangements is stated as:

> The cross slope and crown arrangement of the traveled way may be designed with plane or curved sections, or a combination of the two. The advantage of the curved section is that the cross slope steepens toward the edge of pavement, thereby facilitating drainage at the curb. The disadvantages are that the cross slope of the outer lanes may be excessive, and warping of pavement areas at intersections may be awkward or difficult to effect. Plane sections are more commonly employed on urban arterials.
>
> The cross slope and crown arrangement of the pavement have the very important function of draining the surface. Under certain conditions vehicles will hydroplane, i.e., the condition where one or more tires of a moving vehicle are separated from the pavement by a film of water; usually due to a combination of depth of water, pavement surface texture, vehicle speed, tread patterns, tire conditions and other factors. The chances of hydroplaning are minimized if surface water is rapidly drained.
>
> Pavements for undivided streets regardless of the number of lanes, are normally sloped each way from the centerline.
>
> Pavement sections showing basic cross slope arrangements for divided highways are illustrated in figure H-7. In figures H-7a to H-7d, inclusive, pavements drain laterally each way from a crown line which normally is located on the centerline of each pavement. However, it may be off center initially where provision is made for future widening (figure H-7a), or it may be off center ultimately as a result of adding the extra lanes shown hatched (figure H-7d).
>
> A cross section with a crown on each roadway has a considerable advantage in rapidly draining the pavement during rainstorms. Also, the difference between the low and high point in the pavement cross section is kept to a minimum by the smaller width of pavement sloping in one direction. Change from normal to superelevated cross section can be made with little difficulty. Disadvantages are that more inlets and underground drainage lines are required, with pickup facilities needed at or near both pavement edges, and treatment of at-grade intersections is more difficult due to the several high and low points on the cross section. Such sections, figures H-7a to H-7d, preferably should be used in regions of high rainfall or where snow and ice are factors. Sections without curbs and with a depressed median (figures H-7a and H-7b) are particularly advantageous for these conditions.
>
> Where pavements are sloped in one direction to drain from the median to the outside, the slopes may be pro-

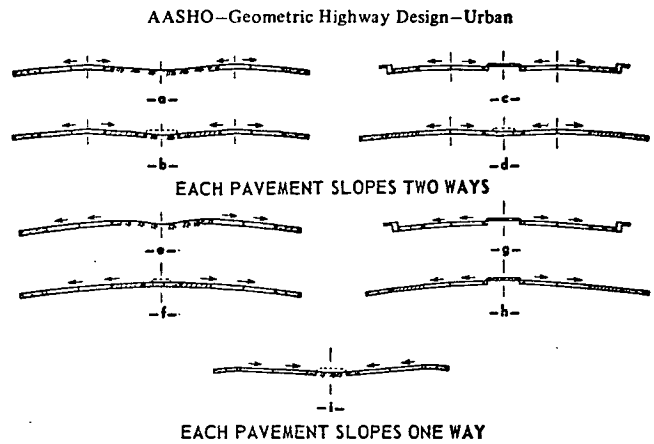
> gressively increased to the outer edge to accelerate the runoff. Where the median drains over the pavements, as in figure H-7f, H-7g and H-7h, savings are effected in drainage structures, and treatment at intersecting streets is simplified. Pavements sloped in the same direction have a more comfortable feeling to drivers since vehicles tend to be pulled in the same direction when changing lanes.
>
> Another possible arrangement (figure H-7i) has a one-way slope on each pavement, but with all lanes draining toward the median. This section has an advantage over sections sloped to the outer edges in that the outer lanes used by most traffic are freer of surface water and there is economy in the drainage system in that all surface runoff is collected into a single conduit under the median. This may be particularly economical on elevated structures. On roadway sections, inward-sloping pavements structurally favor the outer lane that carries most heavy axle vehicles, placing it high instead of low in the total pavement structure and drainage section. The main objection to this arrangement is that all the pavement drainage must pass over the inner lanes. With median curbs, drainage is concentrated next to, and on, the high-speed lanes which results in annoying and hazardous splashing on the windshields of opposing traffic when the median is narrow. Also, additional water on the high-speed lanes increases the possibility of hydroplaning in the flatter areas.
>
> On two-lane pavements crowned in the center, the rate of cross slope for each lane normally should be ⅛ to ¼ inch per foot. When three or more lanes are inclined in the same direction on multi-lane pavements, each successive pair of lanes or portion thereof outward from the first two lanes from the crown line preferably should have an increased slope. The two lanes adjacent to the crown line should be pitched at the normal minimum slope and, on each successive pair of lanes or portion thereof outward, the rate should be increased by about 1/16 inch per foot. However, the slope of the outer lane should not be so steep that it is uncomfortable to drive. In general, it is recommended that the slope in the two lanes adjacent to the crown line be a minimum of ⅛ inch per foot and the maximum slope in the outside lane(s) be ¼ inch per foot.
>
> For operational reasons, the use of cross slopes steeper than ¼ inch per foot on high-type, high-speed pavements with a central crown line is not desirable. In passing maneuvers, drivers must cross the crown line and negotiate a total "roll-over" of more than ½ inch per foot, or a cross slope change of over 4 percent. The reverse curve path of travel of the passing vehicle causes a reversal in the direction of centrifugal force, which force is further exaggerated by the effect of the reversing cross slopes. Trucks with high body loads are caused to sway from side to side when traveling at high speed, at which time steering control may be difficult.

Similarly, on the general topic of drainage on page 385 of DUHAS, policy is stated as:

> As discussed under Pavements and Cross Slopes, arterial highway pavements should be designed with sufficient cross slope to drain rapidly with steeper slopes on the outer lanes. Where pavement surfaces are warped as at cross streets or ramps, surface water should be intercepted before the change in cross slope. Also, inlets should be located just upgrade of pedestrian crossings.

On page 442, under the subject of "Design Elements—Pavements and Cross Slope," policy is stated as:

> Through traffic lanes should be at least 12 feet wide. Nonsuperelevated sections should be sloped a maximum of ¼ inch per foot. Where snow and ice are not of concern, two-lane pavements usually are sloped to drain the full width of the roadway. On wider facilities, particularly in areas of heavy rainfall, transverse drainage may be two-way on each traveled way, with the crown located at one-third or one-half the total width from one edge. In snow areas, transverse drainage should be two-way on each traveled way so that snow stored in the median will not melt and drain across the traveled way, or the median should be designed to prevent this from happening.



ROADWAY SECTIONS FOR DIVIDED HIGHWAYS
BASIC CROSS SLOPE ARRANGEMENTS
Figure H-7

In summarizing the various sections in the AASHTO publications concerning satisfactory cross slope for drainage, it can be concluded that anything between 0.008 and 0.0208 ft/ft is adequate. No data are given to support this range of values, however, except in the sense that this range represents common practice. Later parts of this section will deal more specifically with the governing factors, such as pavement width, rainfall rate, and pavement skid resistance, which should be considered in specifying adequate cross slope for drainage.

The remarks pertaining to the influences of pavement width on drainage (pp. 349 through 351 of the DUHAS) suggest that the pavement should be sloped at a progressively increasing rate from the median side to the outside, where the median drains over the pavement. Similar recommendations are made for crowned pavements having three or more lanes inclined in the same direction. In light of the findings of this study, careful consideration should be given to inclining all lanes at the same maximum rate. This consideration is particularly important on curved sections of highway. The superelevation rate should be chosen on the basis of pavement width, degree of curvature, local rainfall conditions, and a projected value for pavement skid resistance.

Specific Cross-Section Design Considerations for Drainage

From the findings reported here, it is clear that drainage width and superelevation are the primary factors influencing surface drainage on highway cross sections. Surface texture has a lesser effect, and grade (if the curve is on a grade) has little influence. The importance of drainage in curve design can be appreciated by considering the fact that an increase in water depth from 0.02 in. to 0.04 in.

can mean a drop of six or seven skid number units in effective pavement skid resistance. If the water reaches a depth of 0.10 in. to 0.15 in., hydroplaning is likely. All cross sections should be designed to limit the depth of surface water to a maximum value. If it is likely that this maximum will be exceeded, pavement skid resistance should be increased as a compensating measure.

As indicated earlier, the design variables important in controlling water depth are the drainage length, L, and the superelevation, e. On a curve, the drainage length is equal to the travelway width plus the width of the paved shoulder on the high side of the curve, if it is sloped in the same direction as the travelway. Pavement water depth can be essentially expressed in terms of rainfall rate, I, and the single parameter, L/e. If the water depth is to be limited to a maximum permissible value, the design parameter, L/e, becomes primarily a function of the rainfall rate.

Figure 14 shows water depth as a function of a drainage design parameter, $K(L/e)$, and rainfall rate. This figure is a graphical representation of Eq. 4 and, accordingly, provides conservatively large water depth predictions. Three curves are shown on the plot, one each for water depths of 0.02 in., 0.04 in., and 0.06 in. A maximum design water depth of 0.02 in. is desirable, since this is the standard depth generally used in pavement skid testing (*11*). However, if the rainfall rate exceeds 0.025 in./hr., Eq. 4 predicts water depths greater than 0.02 in. even for typical tangent sections (e.g., see Table 12); thus curves for other maximum design water depths are included. If a water-depth value greater than 0.02 in. is used in design calculations, the skid resistance of the pavement should be adjusted to compensate for the additional water depth.

Figure 14 is divided into four parts. In the "Acceptable" region, where the design water depth is 0.02 in., or less, an increase in skid number is not needed. The increases recommended for other parts of the figure are given in Table 14. Note that design water depths greater than 0.06 in. are not recommended because hydroplaning may occur at these depths. Furthermore, it should also be noted that the recommended skid number increments are based on (1) a limited amount of tire data and (2) speeds approaching 80 mph.

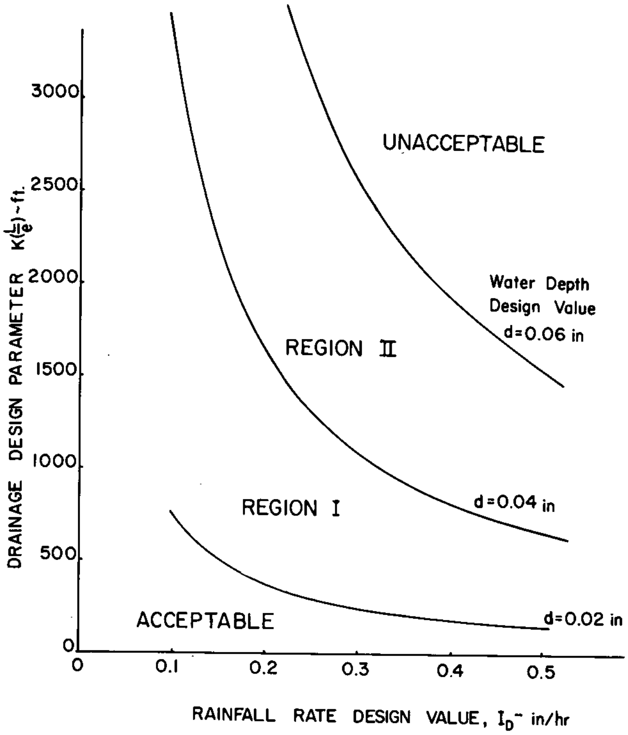


Figure 14. Drainage considerations in safe cross-section design.

TABLE 14

SKID RESISTANCE INCREMENT VS. DESIGN WATER DEPTH

Region on Figure 14	Design Water Depth, d(in.)	Skid Resistance Increment, SN_D (Skid Number Units)
Acceptable	0 - 0.02	0
Region I	0.02 - 0.04	7
Region II	0.04 - 0.06	13
Unacceptable	> 0.06	Not Recommended

To use Figure 14, a rainfall rate design value must be selected and the quantity $K(L/e)$ must be computed. It is suggested that rainfall rates between 0.25 and 0.50 in./hr be used for design purposes if local precipitation experience is not available. Rates greater than these values are relatively uncommon, cause reduced visibility, and hence a reduction in traffic speed. The increased water depth and resulting loss in friction accompanying very high rainfall intensities are, thus, partly compensated by lower speeds and the correspondingly reduced friction demand of the traffic. Note that the parameter, $K(L/e)$, is solely a function of the design of the cross section. K is related to the over-all slope of the surface and can be determined from Figure 15.

The use of Figures 14 and 15 in evaluating the design of a cross section is illustrated by the following example:

A Curved Section

Site Characteristics:

Width of Roadway = 24 ft
Width of Superelevated Shoulder = 10 ft
$e = 0.0156$ ft/ft
G = 3 percent
$I_D = 0.25$ in./hr

It follows that $S = 0.0338$, $K = 1.26$, $L = 30.5$ ft (namely, the distance from the edge of the paved shoulder to the right-wheel path in the right lane), and $K(L/e) = 2{,}460$ ft. With the assumed value of I_D and the previously calculated value of $K(L/e)$, the design falls within Region II of Figure 14. Thus, on the basis of drainage considerations alone, and the models developed by this study, the skid number at the site should be 13 SN units greater than that required on a section where the maximum expected water depth is 0.02 in.

It is clear that pavement drainage can, in principle, be considered in cross-section design. It follows that if drainage is inadequate, pavement friction should be increased correspondingly, provided water depths have been limited to prevent hydroplaning.

Surface Friction Requirements

The skid number needed at a curve/grade site to provide a margin of safety adequate to perform a maneuver induced by a traffic conflict was specified in Eq. 13. This equation has been modified as follows to account for the influence of tire characteristics different from that of the ASTM standard tire (the ASTM tire is used as a reference here since it is the standard tire used in pavement skid resistance measurements):

$$SN_{CG} = \frac{SN_T + 100(\bar{f} + G'')}{T_F}$$

where T_F is a factor to relate operational tire characteristics to the ASTM standard tire. The foregoing equation can be rewritten to emphasize the required skid number, measured at 40 mph, for safe travel at velocity V. The result is:

$$SN_{(40/V)CG} = \frac{SN_{(40/V)T} + 100(\bar{f} + G'')}{T_F} \qquad (14)$$

where V is a characteristic velocity near the maximum velocity that vehicles travel on the given highway section (examples are the speed limit, the highway design speed, or the 90th percentile of the speed distribution on the section), and $SN_{(40/V)T}$ and $\bar{f}$ are functions of V.

Values of $SN_{(40/V)T}$ should be selected to reflect safe driving experience on tangent sections. Acceptable values can be determined from the V_{LOC} curves in Figure 9, if these results are extrapolated to remove the influence of grade and curvature. Through a process of normalizing the data in Figure 9 for tire tread depth and skid number gradient, it can be shown that for characteristic velocities V (*equal to* V_{LOC}) greater than 50 mph:

$$SN_{(40/V)T} \doteq 4 + (0.2 - SN_{grad})(V - 40) \qquad (15)$$

where SN_{grad} is the skid number gradient, SN/mph (note that SN_{grad} is almost always negative). Substituting Eq. 15 into Eq. 14 yields

$$SN_{(40/V)CG} = \frac{4 + 100(\bar{f} + G'') + (0.2 - SN_{grad})(V - 40)}{T_F} \qquad (16)$$

Eq. 16 does not include a skid number margin for pavement drainage deficiencies. To provide a safety margin for pavement drainage, the skid number increment presented in the previous section can be added to the results expressed by Eq. 16; thus

$$SN_{(40/V)CG} = \frac{4 + 100(\bar{f} + G'') + (0.2 - SN_{grad})(V - 40)}{T_F} + SN_D \qquad (17)$$

where SN_D is the skid number increment needed to overcome drainage deficiencies. This is the desired relationship for skid number requirements.

It should be understood and emphasized that Eq. 17 represents a conservative interpretation of the findings of this program. Future research and experience may provide the basis for suggesting lower values of skid number than those determined by Eq. 17. This equation is intended to provide a relatively straightforward means for making comparative evaluations of existing or proposed sections of main rural highways where the selected characteristic velocity is in the range from 60 to 80 mph. (An alternative simpler analysis, which does not include (1) the use of a tire factor or (2) an estimate of the acceptable skid resistance of a tangent section, has been performed in connection with the findings previously presented in Table 12.)

Values of T_F for use with Eq. 17 should be based on minimum tread depth traction conditions. To be completely conservative, this would mean a T_F value for smooth tires. However, the value of $SN_{(40/V)CG}$ that would result is considered to be impractical. Therefore, T_F values corresponding to the legal minimum of tread depth are probably more realistic. Values of T_F for specific tread depths characteristic of legal minimums in most states are included in Table 15 (*12*).

In summary, Eq. 17 provides a means for determining pavement skid resistance requirements for curve, grade, or curve/grade sites. The equation is based on (1) the skid resistance required for safe maneuvering on tangent sections; (2) additional increments in skid resistance to com-

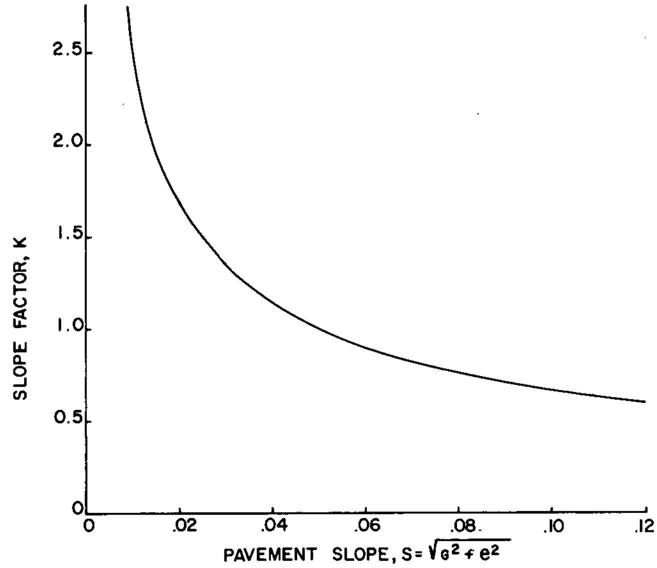


Figure 15. Slope factor versus pavement slope.

TABLE 15

VALUES OF T_F FOR SPECIFIC TREAD DEPTHS

Tread Depth, in.	T_F
$\frac{0}{32}$ (worn smooth)	.29
$\frac{1}{32}$	.40
$\frac{2}{32}$	.50
$\frac{3}{32}$	.60
$\frac{4}{32}$	.69
$\frac{6}{32}$ (half worn)	0.85
ASTM Tire	1.00
$\frac{12}{32}$ (new tire)	1.20

pensate for curvature and grade; (3) pavement surface drainage factors; and (4) a tire tread-wear factor.

Two examples of the use of Eq. 17 to specify skid resistance requirements are as follows:

Case 1—Curved Section of Pavement with Moderate Superelevation

Site Characteristics:

Width of Roadway = 24 ft
Width of Superelevated Shoulder = 10 ft
$D = 1°$
$e = 0.0313$ ft/ft
$G'' =$ 3-percent downgrade
$V = 80$ mph
$I_D = 0.25$ in./hr
Tire Tread Depth = 2⁄32 in.

Derived Quantities:

$S = 0.0434$
$K = 1.07$
$L = 30.5$ ft
$K(L/e) = 1{,}042$ ft
SN_D (Region I) $= 7$
$\bar{f} = 0.043$
SN_{grad}(Assumed) $= -0.5$ SN units/mph
$T_F = 0.50$

Substituting the foregoing derived quantities into Eq. 17 yields:

$$SN_{(40/80)CG} = \frac{4 + 100(0.04 + 0.03) + (0.2 + 0.5)(80 - 40)}{0.5} + 7 = 85$$

Thus, for a vehicle traveling at 80 mph with tires with 2⁄32 in. of tread, in a rainstorm of 0.25 in./hr rainfall rate, the required value of SN_{40} for safe travel is 85. If the tires have full tread depth ($T_F = 1.2$), the corresponding value is 40.

Case 2—Curved Section of Pavement with Large Superelevation

Site Characteristics:

Same as Case 1, except that
$e = 0.0625$ ft/ft
Width of Superelevated Shoulder = None

Derived Quantities:

$S = 0.0693$
$K = 0.83$
$L = 20.5$ ft
$K(L/e) = 272$ ft
$SN_D = 0$
$\bar{f} = 0.012$
$SN_{grad} = -0.5$ SN units/mph
$T_F = 0.50$

Substituting the foregoing derived quantities into Eq. 17 yields a required SN_{40} value of 60. Thus, by doubling the superelevation and shortening the drainage length, the required skid number has been reduced from 85 to 60. Again, for fully treaded tires, the required SN_{40} value is 25. Thus, if the skid resistance were made adequate for a 2⁄32-in. tread, a margin of 35 SN units would be available when fully treaded tires are used.

Eq. 17 provides a practical means for determining the skid number requirements for a given section of roadway. It is evident that geometry, drainage, and tire usage enter into pavement friction requirements, and that these factors lead to different friction needs on different sections of pavement.

Maneuver Considerations in Roadway Design

Equally important to providing adequate pavement skid resistance is the need for reducing the demand for skid resistance by reducing severe vehicle maneuvering at a site. The main factors influencing the need for severe maneuvering are signing, sight distance, roadway discontinuities (i.e., interchanges, rest stops, lane drops, etc.), traffic density, and driver responsiveness. The interaction between these variables is quite complex and is not fully understood. It is important, therefore, that the existing design guidelines, such as those in the AASHTO geometric design manuals (*2, 3*) and the *Manual on Uniform Traffic Control Devices for Streets and Highways* (*13*), be adhered to as carefully as possible.

In evaluating a new section of road, a design review policy is required, which can be used to define a running record of the maneuver demand potential throughout the length of the roadway. Such a record would be similar to that currently used for recording sight distances on plans (*2, 3*). The factors to consider in constructing a running record of maneuver demand potential are as follows:

1. The cues that must be assimilated to carry out a decision (e.g., signing, pavement markings, delineators, other vehicles, etc.).

2. The cue obstructions (e.g., embankments, foliage, ambiguous sign messages, limited sight distance, etc.).
3. The complexity or number of choices in the decision process.
4. The time available for making the decision.

Along with the establishment of this record, criteria need to be established for limiting the maneuver demand potential for various classes of geometrics. The criteria and the record should then be used in combination as a design control mechanism.

Although it is possible to outline the basic requirement for a design review procedure to establish a maneuver demand potential, the specific development of such a procedure is well beyond the scope of the present project. However, project findings have clearly demonstrated a need and priority for developing such a procedure.

SITE IMPROVEMENTS

A form to be used in identifying the accident causation factors at existing highway sites is given in Appendix F. Since it is intended for use in field investigations, the form is divided into two parts—a site description form and a site evaluation checklist. The site description form is structured to provide a detailed description of the pertinent site characteristics. The site evaluation checklist is divided into eight parts:

1. Ambience factors.
2. Geometric factors.
3. Traffic barrier factors.
4. Illumination factors.
5. Roadway maintenance factors.
6. Marking factors.
7. Unguarded hazard factors.
8. Signing factors.

Most sections of the checklist have two columns, on the right-hand side, that are labeled "Presence" and "Accident-Causation Factor." This allows the presence of an item to be noted even though the item may not be an accident-causation factor. The "Accident-Causation Factor" column has been placed at the extreme right to facilitate a rapid review of the checklist. The intent of the list is to provide a rapid and efficient means of identifying the need for specific site improvements.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

Based on the combined findings from (1) an extensive analysis of accident data, (2) computer simulation studies, and (3) an indepth field investigation of two high-accident sites, it has been concluded that drivers are not likely to lose control of their vehicles on curve-grade sites unless they are attempting to perform severe maneuvers on slippery road surfaces with fair-to-poor tires. The AASHTO design procedures—as described in *A Policy on Geometric Design of Rural Highways, 1965* (GDRH) and *A Policy on Design of Urban Highways and Arterial Streets, 1973* (DUHAS)—provide a practical method for arriving at reasonable geometric designs for sites with combined horizontal curvature and vertical grade, provided (1) the selected values of superelevation are large enough to result in adequate pavement surface drainage and (2) the pavement skid resistance is sufficient for anticipated vehicle maneuvering. However, misinterpretation of the AASHTO design procedures has resulted in design and construction of long-radius curves with inadequate superelevation for surface drainage that contributes to an extraordinary wet-weather accident rate at this type of site.

The report recommends compliance with the design superelevation values for various degrees of curvature and design speeds found in Tables III-7 to III-10 in (GDRH) and attention to roadway geometry, signing, and maintenance practices to reduce severe maneuvers on curves. It also contains a proposed procedure for determining pavement skid resistance requirements for curves. The recommendations for increasing superelevation and for reducing severe maneuvers at curve sites are based on the combined findings of mathematical simulation studies, rather extensive accident data, and a pavement surface drainage analysis, and thus should be implemented immediately during the design of new highway sections and improvement of existing high-accident sites. The procedures for determining specific pavement skid-resistance requirements for curve sites have not as yet been correlated with accident experience.

The following specific conclusions have been drawn from the findings of each of the major activities of this study:

1. The accident data from the Ohio Turnpike show no statistically significant dependence of the accident rate on grade or curvature except that a specific 1° curve on a 3-percent downgrade has a very high accident rate.
2. The accident rate on the Pennsylvania Turnpike does not depend on grade, but it does increase significantly with increasing side friction factor, that portion of the lateral acceleration developed by vehicles traversing curves that is not accommodated by superelevation.

3. The accident history at the 1°-curve, 3-percent downgrade site on the Ohio Turnpike, identified as being highly overinvolved in the occurrence of accidents, appears to be highly associated with wet pavement and worn tires.

4. The analytical and computer simulation work performed in this study indicates that grades normally encountered on modern roadways are of small influence on predicted vehicle loss of control during maneuvering.

5. The simulation work indicated that an abrupt lane-change maneuver on a curve could result in loss of control at normal highway speeds for passenger vehicles with half-worn tires operating on surfaces with $SN_{40} = 30$ during wet weather.

6. The abrupt lane change and braking maneuver used in this study was such that normal grades and curvatures had only a small influence on the maximum speed at which the maneuver could be performed without loss of control.

7. By using the models developed during this study for estimating pavement skid resistance needs, it was found that highway sites having combined curvature and grade required greater pavement skid resistance than did corresponding tangent sections to provide a similar margin of safety for abrupt lane-change maneuver during wet weather.

8. Pavement surface drainage was found to be an important consideration for safe maneuverability at curve sites during wet weather. The large ratio of total drainage width to superelevation was found to cause unfavorable water depths on some 1° curves as currently designed and built.

9. Methods for evaluating problem sites were developed and used to conclude that (a) a pavement surface drainage problem exists at the problem site selected on the Ohio Turnpike; and (b) many factors, including drainage, short speed-change lanes, insufficient sight distance, and obstructed signs contribute to the high accident rate at the site located on I-95 near Fredericksburg, Va.

SUGGESTED RESEARCH

A procedure for implementing the findings of this program to provide tentative guidelines for reviewing design practices for new sections of highway and for evaluating accident-causation factors at high-accident-rate sites was documented in Chapter Three. However, it appears that some of these findings may have broader implications than the objectives of this program and that they should receive evaluation in a larger context. Accordingly, the methodology and findings developed in this study form the basis for recommending the following research:

1. The concept of a skid number margin of safety to reduce wet-weather accidents at curve sites should be evaluated further. An extensive study of the accident problem existing at curve sites should be made for several highways, using the methods and techniques developed in this program.

2. A water-depth study should be made to (a) resolve the differences in the findings of earlier studies (*6-9*); (b) determine tire longitudinal and lateral force characteristics as a function of controlled water depth and tire wear; and (c) develop means for measuring average water depth on highways during rainstorms.

3. Additional field investigations of high accident curve sites should be made using the site investigation methodology developed in this program to determine the practicality of reducing accident rates by remedial measures that reduce pavement skid resistance needs.

4. Research to define a means of identifying problem sites without waiting for accidents to occur should be undertaken. Possibly, a concept of observed traffic conflicts would provide a reasonable starting point.

5. Additional computer simulation studies should be undertaken to investigate other maneuvers that might cause loss-of-control problems and the potential for skidding on wet pavements. However, a larger amount of detailed information is needed on driver behavior in performing emergency maneuvers in order to reconstruct accident situations. Possibly, the use of event recorders in vehicles on the highway can provide the information needed to study accidents involving steering and braking maneuvers.

6. Procedures should be developed for creating a running record of maneuver demand potential along new and existing sections of roadway.

7. A detailed study of the influences of wind on vehicle handling and traction (i.e., the increased lift and lower tractive forces that result from cross winds) should be undertaken. A cross section of automobile configurations should be examined. The actual wind profiles at the Ohio Turnpike problem site should be measured and used as disturbance inputs to the handling and traction studies.

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