UM-HSRI-PF-74-1

1-14

COPY NO.__________

INFLUENCE OF COMBINED HIGHWAY GRADE AND HORIZONTAL ALIGNMENT ON SKIDDING

FINAL REPORT

VOLUME 1 OF 2

PREPARED FOR

TRANSPORTATION RESEARCH BOARD
NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
NATIONAL ACADEMY OF SCIENCES

BY

DUANE F. DUNLAP
PAUL S. FANCHER
ROBERT E. SCOTT
CHARLES C. MACADAM
LEONARD SEGEL

SEPTEMBER 1974

TABLE OF CONTENTS
PART I

PART II - APPENDICES

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

Mr. Harry Smith served as Project Engineer for the Highway Research Board. Special thanks are surely due to him for his guidance and suggestions throughout this program.

The authors express their appreciation to Mr. Peter DeCamp of the Michigan Department of State Highways and to Professor Donald Cortright of The University of Michigan for serving as consultants to us.

We thank the following individuals for supplying us with information on, or access to, specific highway sites:

Mr. David Mahone, Virginia Highway Research Council
Mr. Charles Radyk, Ohio Turnpike Commission
Mr. George Sherman, California Division of Highways
Mr. Leo Sandvig, Pennsylvania State Highway Department
Mr. Paul Riley, Michigan Department of State Highways

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

Mr. Gary Hu, also of the Institute, prepared the art work for this report.

SUMMARY OF FINDINGS

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 objectives of the study were to (1) examine the factors that influence safe operations on highway sections having combined curvature and grade; (2) determine those operating conditions which 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 modifications to current AASHTO design polices.

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 shows no significant accident dependence on either grade or curvature, except that a specific 1° curve on a 3% downgrade has a very high accident rate. This accident history appears to be highly associated with wet

pavement, and to a 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 which can lead 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 surfaces with a skid resistance of $SN_{40} = 30$. In an emergency lane change and braking maneuver on an $SN_{40} = 30$ surface, 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. Also, worn tires, which are substantially less effective than the ASTM standard tire in wet pavement traction, but which have tread depths which are greater than the legal minimum in some states, must be considered in determining pavement skid resistance requirements. 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% downgrade on the Ohio Turnpike. The other site was located on I-95 near Fredericksburg, Virginia. Likely causes for a high degree of maneuvering exists at the Virginia site due to an interchange with U.S. 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 pavement water depth is primarily a function of total road width and superelevation. Consequently, the margin of wet weather pavement skid resistance available for emergencies is less on curves than on tangents. Grade is a secondary factor in determining pavement water depth.

The overall findings 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 AASHTO design procedures provide a practical method for arriving at reasonable geometric designs for highway sites with combined horizontal curvature and vertical grade, provided that (1) the selected values of superelevation are large enough to result in adequate pavement surface drainage, and (2) the pavement skid resistance is high enough to allow for vehicle maneuvering. In some cases, however, applications of these procedures, as currently stated, have resulted in the design of pavements with inadequate superelevation for surface drainage. The turnpike accident study and field site studies do show, however, that some sites with combined grade and curvature do have an extraordinary number of accidents. In addition to the surface drainage deficiencies that derive from low values of superelevation, the analytical and simulation studies indicate that vehicle maneuvering at curve and curve/grade sites is potentially more hazardous than at tangent sections. Consequently, recommendations are made concerning (1) interpretation of AASHTO design procedures with regard to superelevation and pavement surface drainage; (2) skid resistance requirements for curves and curve-grade sites; and (3) attention to geometric design and signing to reduce severe maneuvers on curves. These recommendations are applicable to the design of new highway sections and can be used for evaluating accident-causation at existing sites.

The basic 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 (see Chapter 3, Equation (15)). Also, a rationale is presented for defining the maneuver demand potential existing 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 (see Appendix F).

DEFINITION OF SYMBOLS

Symbol	Definition
A_x	Longitudinal acceleration
A_y	Lateral acceleration
a	Distance from the vehicle center of gravity to the front axle
a_L	Maximum acceleration in a lane change maneuver
a_{LC}	Approximately equal to the lateral acceleration (in g's) used in a lane change maneuver on an equivalent tangent section of road
BFC	Brake Force Coefficient
BPN	British Portable Number
b	Distance from the vehicle center of gravity to the rear axle
C	Width of lane change maneuver
CI	Confidence Interval
c.g.	Center of gravity
$C_1,C_2,\ldots,C_7,C_9,$ $C_{10},\ldots C_{13}$	Steering control system gains
C_8	Steering ramp time interval (see T_1)
C_1, C_2, C_3	Parametric vehicle designations
$\hat{C}_{ij}$	Predicted crash rate for the cell defined by ith grade level and the jth curvature level
C_L	Aerodynamic lift coefficient
C_s	Longitudinal stiffness of tire
C_Y	Aerodynamic side force coefficient

Symbol	Definition
C_α	Lateral stiffness
C_γ	Camber stiffness
D	Roadway curvature
DUYDFZ	Variation in peak lateral force coefficient (tires) with load
D_1, D_2, D_3	Parametric curvature values
ΔD_j	Incremental contribution to accident rate that is common to all cells with curvature D_j
δD_j	Difference between observed crash rate and μ when grade is zero
d	Water depth
E.B.	Eastbound
Exp	Expected
e	True superelevation
e^*	Apparent superelevation
e_1, e_2, e_3	Parametric superelevation values
Δe_i	Incremental contribution to accident rate that is common to all cells with superelevation e_i
FXGRAD	Gradient of μ_X with respect to slip in high-slip region
F_X	Braking force
F_{XF}	Longitudinal force on front tires
F_{Xi}, F_{Yi}, F_{Zi}	Longitudinal, lateral, and vertical forces, respectively, on the ith tire
F_{XR}	Longitudinal force on rear tires
F_{xw}	Longitudinal force in tire footprint

Symbol	Definition
$F_{x_1}, F_{x_2}, F_{x_3}$	F_x values at a common slip value for vehicles of different weight
F_{YF}	Lateral force on front tires
F_{YFL}	Lateral force on left front tire
F_{YFR}	Lateral force on right front tire
F_{YR}	Lateral force on rear tires
F_{YRL}	Lateral force on left rear tire
F_y	Lateral load on tire
F_{yw}	Lateral force in tire footprint
F_{ZF}	Vertical force on front tires
F_{ZR}	Vertical force on rear tires
F_z	Vertical load on tire
f	Side force factor
$\bar{f}$	Acceleration needed to maintain a curved path
Δf_j	Incremental contribution to accident rate that is common to all cells with side force factor f_j
G	Pavement grade
G'	Magnitude of downgrade
G''	Magnitude of grade for downgrade and zero for upgrade
G_1, G_2, G_3	Parametric grade values
ΔG_i	Incremental contribution to accident rate that is common to all cells with grade G_i
δG_i	Difference between observed crash rate and μ when curvature is zero

Symbol	Definition
g	Gravitational constant
$H, H(p)$	Open loop steering controller transfer function
h	Center of gravity height of vehicle
I	Rainfall intensity
I_D	Rainfall rate design value
$\bar{i}_1, \bar{i}_2, \bar{i}_3$	Unit vectors of i coordinate system
K	Slope factor
K_1	Control loop gain
$\bar{k}_1, \bar{k}_2, \bar{k}_3$	Unit vectors of k coordinate system
L	Pavement width
L.O.C.	Loss Of Control
L_c	Length of curve
L_f	Length of flow path
L_s	Length of spiral
ℓ	Wheel base of vehicle
M.P.	Milepost
M_s	Mass of sprung mass of vehicle
M_{zw}	Aligning moment in tire footprint
M_1, M_2	Mass of front unsprung masses of vehicle
M_3	Mass of rear unsprung mass of vehicle
$\bar{m}_1, \bar{m}_2, \bar{m}_3$	Unit vectors of m coordinate system
N	Normal force on vehicle
N/A	Not Applicable

Symbol	Definition
n	Number of data cells in regression model
Obs.	Observed
p, q, r	Roll, pitch and yaw rates of vehicle, respectively
R	Radius of curve
Res	Residue
$(RPS)_i$	Rotation rate of ith wheel
R_c	Radius of curvature of roadway
R_o	Radius of the centerline of the road
r	Correlation coefficient
r_s	Spearman's rank correlation coefficient
ΔR	Command deviation from nominal path
S	Pavement slope
SBL	Southbound Lane
$S_1, S_2, \ldots S_5$	Parametric surface designations
S_{LF}	Left front wheel slip
S_{LR}	Left rear wheel slip
S_{RF}	Right front wheel slip
S_{RR}	Right rear wheel slip
$SE_{\Delta Dj}$	Standard error of the estimates of ΔD_j
$SE_{\Delta ej}$	Standard error of the estimates of Δe_j
$SE_{\Delta fj}$	Standard error of the estimates of Δf_j

Symbol	Definition
$SE_{\Delta Gi}$	Standard error of the estimates of ΔG_i
SE_{μ}	Standard error of the estimates of μ
SN	Skid number
SN_C	Improved skid number required for a curve site
SN_{CG}	Improved skid number required for a combined curve-grade site
SN_D	Skid number increment for overcoming water depth on pavement
SN_G	Improved skid number needed for a grade
SN_{grad}	Skid number gradient
SN_V	A safe skid number for level tangents at velocity, V
$SN_{V_{LC}}$	Required skid number on a tangent at V_{LC}
SN_{40}	Skid number at 40 mph
$\overline{SN}_{40}$	Minimum allowable skid number at 40 mph
SN_{40CG}	Improved skid number required at combined curve-grade site at 40 mph
SN_{40S}, SN_{30S}, SN_{60S}	Skid number values determined by the Schonfeld Method at 40, 30, and 60 mph, respectively
SN_{40T}	SN_{40} value needed on a tangent section
SN_{40Tr}	SN_{40} value measured by a skid trailer
s	Single-vehicle crashes
s'	Longitudinal slip
T	Time and pavement texture depth

Symbol	Definition
T_F	Gross factor relating tires in use to ASTM tire
T_1	Steering ramp time interval (see C_8)
t	Total crashes
u, v, w	Longitudinal, lateral and vertical velocities, respectively, of vehicle sprung mass
V	Vehicle velocity
V.C.	Vertical Curve
V_{CR}	Limiting safe velocity for cornering with drive thrust applied as necessary to maintain speed
V_{LC}	Limiting safe velocity for a cornering vehicle which also performs a lane change with drive thrust applied as necessary to maintain speed
V_{LOC}	Maximum initial velocity from which a combined lane change and abrupt stop can be performed without loss of control
V_m	Vehicle miles in units of 10,000 miles
V_{SL}	Speed Limit
W	Weight of vehicle
W.B.	Westbound
W_1, W_2, W_3	Vehicles of different weights
X, Y, Z	Vehicle fixed coordinate system
X', Y', Z'	Space fixed coordinate system
$\vec{X}_1$	Vector defining highway grade for discrete intervals
$\vec{X}_2$	Vector defining highway curvature for discrete intervals

Symbol	Definition
x, y	Vehicle path coordinates
Y_a	Number of accidents predicted by regression equation
Y_F	Feedback loop transfer function
$\hat{Y}_{ij}$	Expected accident rate for the cell defined by grade $G_i (i=1,2,\ldots,7)$ and curvature $D_j (j=1,2,\ldots,8)$
Y_o	Forward loop transfer function
Y_p, Y_{C_1}, Y_{C_2}, Y_δ, $Y_{r,\delta_{FW}}$, $Y_{\gamma,r}$	Steering control transfer functions
Y_p	Predicted path deviation
Z, R, θ	Cylindrical coordinate system for describing combined curve-grade
α	Specified limiting confidence value for a Type I error
α'	Lateral slip angle
β	Vehicle sideslip angle
γ	Path angle of vehicle velocity vector
γ'	Inclination (camber) angle of wheel
Δ	Roadway curve increment, including transitions
Δ_c	Roadway curve increment, circular portion only
δ_{FW}	Vehicle front wheel angle
δ'_{FW}	Commanded front wheel angle
δ_{sw}	Steering wheel angle
δ_1, δ_2	Vertical deflections of front unsprung masses

Symbol	Definition
δ_3	Vertical deflection of rear unsprung mass
ε	Error
η	Braking efficiency
Θ_s	Spiral curve increment
λ	Steering path error
λ'	Lead compensated steering path error
μ	Contribution to the total accident rate that is common to all cells of the regression matrix
μ'	Maximum coefficient of friction produced by either front or rear tires
μ_F	Coefficient of friction for front wheels
μ_R	Coefficient of friction for rear wheels
$\mu_x\Big\|_{v=40}^{s=1}$	Locked wheel coefficient of friction at 40 mph
$\mu_x\Big\|_{v=80}^{s=1}$	Locked wheel coefficient of friction at 80 mph
μ_{xp}	Maximum longitudinal coefficient of friction
μ_{xs}	Locked wheel coefficient of friction
μ_{yp}	Lateral coefficient of friction at 3° slip angle
ρ	Correlation coefficient
ϕ_R	Roll angle of rear unsprung mass
ψ	Vehicle heading angle
ψ_f	Steer angle at front wheel

Symbol	Definition
ψ_p	Desired vehicle path angle
℄	Centerline
$(\dot{\ })$	Denotes differentiation with respect to time

CHAPTER 1

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 Cooperative 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 overall accident problem involving vehicle operation on highway sections containing both curvature and grade (upgrade or downgrade). The principal objective of this research has been 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 objectives, called out in the NCHRP project statement, are 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

    1) Grades
    2) Superelevation rate and runoff
    3) Radius and type of horizontal alignment
    4) Pavement surface properties and conditions
    5) Drainage

B. Vehicle and Operation Characteristics

    1) Operating speeds and lateral acceleration
    2) Braking and longitudinal acceleration
    3) Weight, geometry, suspension and related factors
    4) 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. Due to this fact—coupled with the limited available funds for Project 1-14—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 Objectives 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."

To achieve the principal objective, a plan was adopted which addressed the specific objectives by dividing the research into six (6) tasks. These tasks are enumerated below and the type of work performed in each task is briefly summarized.

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 HVOSM* simulation was applied to determine those roadway and vehicle factors that can lead 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 (1) equilibrium cornering, (2) lane changes, and (3) 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 (1) combined horizontal and vertical alignment and (2) high accident experience, were selected and studied to identify those characteristics which have 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

---

*The letters HVOSM are used to designate a generally available mathematical simulation developed by McHenry, et al. (1).

accident data analyses (Task 1) were combined with results predicted by simulation to determine the conditions which 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 have been 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 the next chapter of this report. These findings have been organized into the following categories:

1) Accident Data Analysis
2) Vehicle Loss-of-Control Analysis
3) Pavement Drainage
4) Selection and Evaluation of Problem Sites
5) Design Policy Analysis

Interpretations and applications of these findings are discussed in Chapter 3. Conclusions are stated in Chapter 4. Part II of this report contains several appendices which provide detailed documentation of the work done to produce the findings presented in Chapter 2.

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.

CHAPTER 2

FINDINGS

The findings of this program are presented in this chapter. Separate sub-sections entitled Accident Data Analysis, Vehicle Loss-of-Control Analysis, Pavement Drainage Analysis, Selection and Evaluation of Problem Sites, and Design Policy Analysis describe the results obtained in each of the areas indicated by these titles.

The findings and results presented in this chapter are combined and interpreted in Chapter 3 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.

2.1 ACCIDENT DATA ANALYSIS

2.1.1 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 and side friction factor. The Ohio Turnpike shows no significant accident dependence on either grade or curvature, except that a specific 1° curve on a 3% downgrade has a very high accident rate. This accident history appears to be highly associated with wet pavement, and 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'-1°49' in Pennsylvania also have a somewhat higher incidence of wet-pavement crashes than do curves of other curvatures.

2.1.2 TURNPIKE ACCIDENT DATA STUDIES

2.1.2.1 Effects of Horizontal and Vertical Alignment Upon 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 covers a two-and-one-half-year period starting in 1966, and consists of records on 9,822 mainline accidents. Four and one-half years of highway operations on the Ohio Turnpike beginning in 1966 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 in arc minutes of degree of curvature was combined with each accident record and merged with the traffic data. Similarly, horizontal alignment in percent grade and superelevation were 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 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 seven levels, and horizontal alignment into eight to thirteen 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.

The two highways have quite different overall accident experience. On the Ohio Turnpike the overall accident rate is 96 accidents per 10^8 vehicle miles, while 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 which 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.* The latter was computed from

---

*Note that Item (3) is sometimes referred to as "side friction factor" in AASHTO design policy (2, 3). See Equation (6).

curvature, superelevation rate, and speed equal to the posted legal limit. This quantity will be called the "side force factor," and the symbol $\underline{f}$ will be used to represent this quantity.

Table 2-1 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 which is explained by the regression model. Thus the model with eight levels of curvature explains 65% of the variability in Ohio and 60% in Pennsylvania, while the use of eleven levels of curvature in the latter explains 67%. 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% of the variability.

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

Accident-causation factors not explained by the additive alignment model would be expected to result

TABLE 2-1

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

in observed rates outside the confidence intervals with a probability of 0.05. Therefore, such occurrences would be expected in 5% of the combinations of grade and horizontal alignment. This proportion was exceeded in all models, and by a factor that indicates significant unidentified "error" sources. The individual cells which have residuals representing real differences versus chance consequences of random error cannot be uniquely identified. However, interaction between grade and horizontal alignment is not evident.

The results of the regression models are given in detail in Appendix A, and the principal findings are depicted graphically in Figures A-1, A-2 and A-5, A-6 for the eight-level curvature model applied to the Ohio data and the eleven-level model applied to the Pennsylvania data, and in Figure A-11 through A-14 for the side-force-factor model. Results are given in each figure for all accidents and for single-vehicle and wet-pavement accidents.

The intervals of side force factor used for the side force models are indicated by the horizontal bars below the abscissa.

The regression analysis indicates no statistically significant and problematical dependence of accident rate upon grade except at the steeper downgrades

(-2.5 to -3%) in Ohio. There are moderate but significant reductions of single-vehicle accident rates on the steeper upgrades, and on wet-pavement accidents on downgrades of about 1% in Pennsylvania. Both turnpikes show a 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 higher side force factors as well as higher curvatures than the Ohio Turnpike, the accident rates are higher in Pennsylvania point-by-point at all curvatures and side force values. Thus the side-force-factor model fails to explain the substantial differences between the two highways.

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% 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 at milepost 166.4-166.7. This location is a 1° curve on a 3% downgrade. The accident rate in this 0.3-mile segment was 665 accidents/10^8 vehicle miles over the 4-1/2-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 indicates that from July 1970 to April 1973—a 34-month period subsequent to the 4-1/2-year period—the accident rate was 559 accidents/10^8 vehicle miles. 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 in Section 2.4.1.

2.1.2.2 Environmental Factors. Several factors were examined relative to their association with accident rate and grade and curvature, viz, (1) surface conditions; (2) number of vehicles involved in the accident; and (3) illumination. Weather was not included because it was found that surface conditions are a surrogate for weather.

Table 2-2 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 of 0°44'-1°5' and on downgrades of

TABLE 2-2

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.

2.5-3.5% are occurring on wet pavements. Wet-pavement accidents are over-represented 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 is given in Table 2-3. The relative incidence of wet-surface accidents does not vary significantly with grade in Pennsylvania. A high proportion of wet-weather accidents do occur on curves of 0°44'-1°49' on the Pennsylvania Turnpike.

Table 2-4 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 Table 2-5 shows some variation of single-vehicle accidents on the Pennsylvania Turnpike, no consistent pattern is observed.

Both turnpikes have the highest relative incidence of 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.

TABLE 2-3

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.

TABLE 2-4

SINGLE VERSUS MULTI-VEHICLE ACCIDENTS
OHIO TURNPIKE

Degree of Curvature	Number of Accidents	Percent: Single Vehicle	Percent: 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	Number of Accidents	Percent: Single Vehicle	Percent: Multi-Vehicle
+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 2-5

SINGLE VERSUS MULTI-VEHICLE ACCIDENTS
PENNSYLVANIA TURNPIKE

		Percent:	
Degree of Curvature	Number of Accidents	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

A distribution of accidents categorized by the presence of daylight or darkness is shown in Tables 2-6 and 2-7. 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. The relative incidence of day versus night accidents is likely a characteristic of exposure.*

2.1.3 CAUSATIVE FACTORS AT HIGH-ACCIDENT SITES. The highway alignment geometrics identified as high-accident sites by the regression analysis are the 1° curves and 2.5-3% downgrades on the Ohio Turnpike and the 4°13'-6° curves on the Pennsylvania Turnpike. One-way analyses of variance of numbers of accidents at these alignments against other alignments were run using the variables in each file which are related to causation as control variables. Summaries of the results are given in Tables 2-8 through 2-10. The significance level given in each table as a percent is the probability that differences as great as those observed would result from chance along. If the significance level is less than 5%, the differences are usually interpreted as real.

---

*Reliable data on hourly traffic patterns is not available. Toll records are not maintained with hourly information.

TABLE 2-6

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 2-7

ACCIDENT EXPERIENCE BY ILLUMINATION
PENNSYLVANIA TURNPIKE

Degree of Curvature	Number of Accidents	*Percent: Daylight	*Percent: 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	Number of Accidents	*Percent: Daylight	*Percent: Darkness
+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.

TABLE 2-8

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

---

*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.

TABLE 2-9

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

---

*See footnote at bottom of Table 2-8 for the meaning of the terms "high" and "low."

TABLE 2-10

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 2-8 for the meaning of the terms "high" and "low."

The results shown in Table 2-8 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 2.5-3% downgrades in the Ohio Turnpike (Table 2-9), rain and wet pavement 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 over-represented.

Table 2-10 gives the analysis of variance for curves of 4°-13'-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 4-6° curves of the Pennsylvania Turnpike are also on grades of from 2.5-3.5%, 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 4-1/2-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 pavement for the entire accident population of each turnpike is shown in Table 2-11. 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 are found in wet-surface accidents than would be expected from the distribution of accidents.

TABLE 2-11

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

The differences are significant at the 0.0% 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.

2.2 VEHICLE LOSS-OF-CONTROL ANALYSIS

2.2.1 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 quasi-static analysis of cornering on a downgrade. A detailed presentation of the entire analysis is given in the first part of Appendix B.

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 following three maneuvers could be performed: cornering under traction, cornering and lane changing, and cornering plus lane changing combined with braking. The HVOSM (Highway-Vehicle-Object Simulation Model) program (1) was used to perform this parametric study. Auxiliary programs were written to (1) produce tire/surface characteristics in a suitable form for input into the HVOSM friction tables; (2) calculate terrain tables suitable for representing superelevated curve/grade sites in the simulation model; and (3) 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. This section presents the analytical results, followed by a summary of the findings of the simulation study.

2.2.2 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 $(\frac{1}{R})$ (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 which cannot be balanced by the saturated rear tires. Consequently, the vehicle has an unbalanced yaw moment which 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 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 using the results of the quasi-static analysis of cornering on a downgrade, presented in Appendix B. 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:

$$\text{Lateral Force:} \quad F_{YF} + F_{YR} = \frac{W}{g} \frac{V^2}{R} - We \tag{1}$$

$$\text{Yaw Moment:} \quad a\, F_{YF} - b\, F_{YR} = 0 \tag{2}$$

where

F_{YF} is the lateral force from both front tires

F_{YR} is the lateral force from both rear tires

W is the weight of the vehicle

R is the radius of the turn

e is the superelevation

a is the distance from the vehicle center of gravity to the front axle

b is the distance from the vehicle center of gravity to the rear axle

g is the gravitational constant

Note that grade does not enter into these simplified equations, since 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 Equation (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.

2.2.3 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 principal outcome of the pilot study was to exclude the following factors from the parametric study: (1) road perturbations, such as traversing a bump or tangent (non-spiral) superelevation transition; and (2) wind effects, such as gusts or a strong, steady cross-wind. These external inputs to the vehicle were found to cause a less significant control problem than a requirement to perform an emergency maneuver. For example, a bump traversal on a curve/downgrade was not found in the simulation to produce loss of control, whereas a lane change under the same circumstances did produce loss of control. In this specific instance, the bump represented a two-inch buckling of the pavement in a total span of six feet. Similar results were obtained for a non-spiral superelevation transition and for two types of cross-wind disturbances: a 30-mph wind plus a 20-mph gust, and a 60-mph wind.

The simulation model does not include the process whereby the profile of the road surface influences the response of the steering system. In addition, the vehicle controller designed to simulate the driver would not have responded to torques at the steering wheel even if these torques had been calculated. Consequently, the simulation results for bumps and superelevation transitions do not include any control problems which result from driver errors due to misleading steering loads or cues. Also, the wind loads were simulated <u>only</u> in the sense of applying lateral forces to the center of gravity of the vehicle. These loads had no substantial effect on vehicle stability. Applying a complete field of aerodynamic forces and moments to the vehicle would have required modeling and data acquisition activities well beyond the scope of this program. As indicated by the pilot study results, the addition of these wind factors, as simulated, would not have a large influence on the study of curve/grade accident factors, although aerodynamic lift forces, by altering the normal loads on the tires, could conceivably decrease the maximum side forces that can be produced by the tires or otherwise upset the balance of yaw moments on the car. Aerodynamic side force could produce similar effects. Wind factors are discussed more fully in Appendix D.

With road surface perturbations and wind effects deleted, 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%, 3%, and 6%
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.

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}	is the limiting safe velocity for cornering with drive thrust applied as necessary to maintain constant velocity
V_{LC}	is the limiting safe velocity for a cornering vehicle which also performs a nine- to twelve-foot lane change while drive thrust is applied to maintain a constant velocity
V_{LOC}	is the maximum initial velocity from which a combined lane change and abrupt stop maneuver can be performed without loss of control.

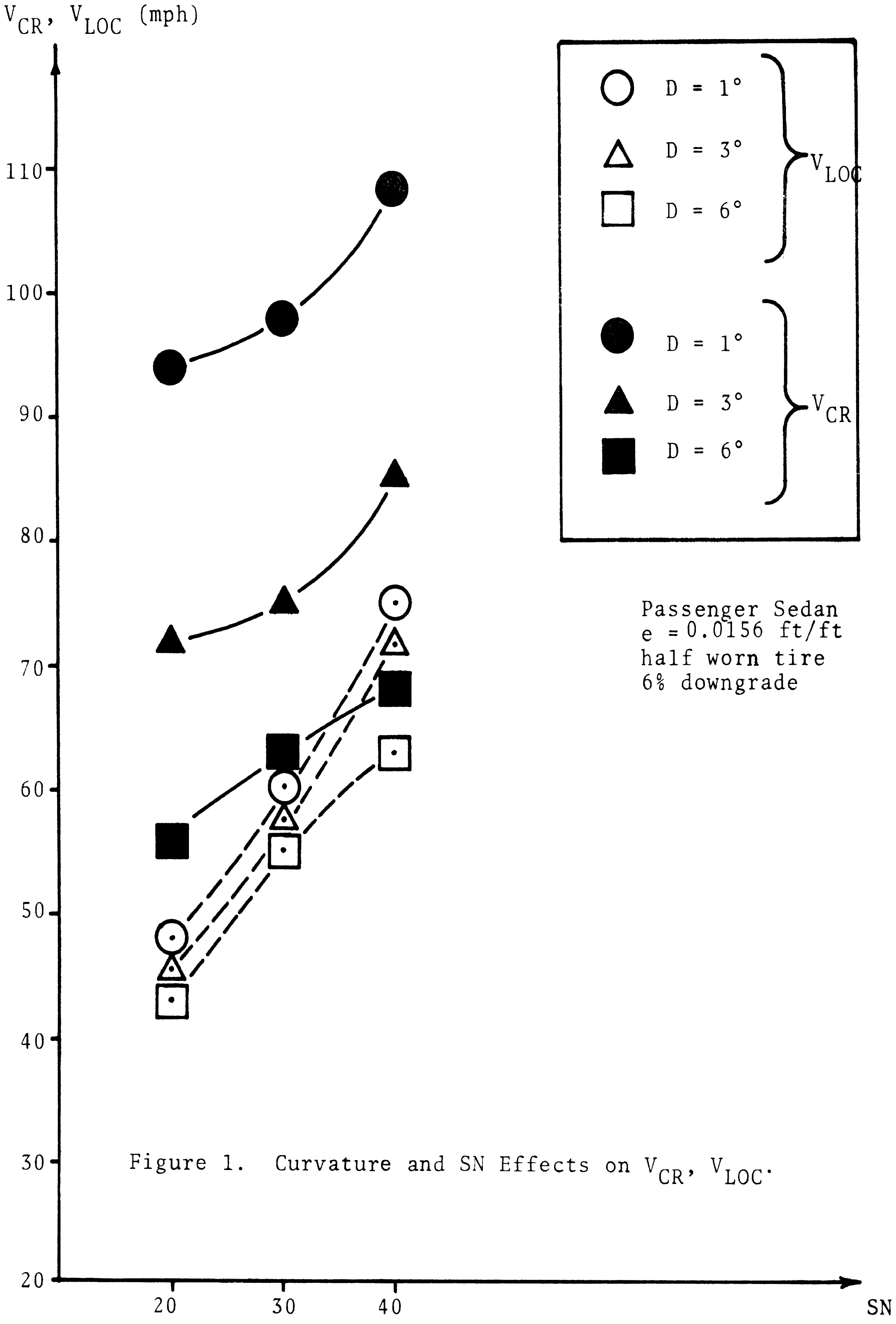
To appreciate fully the results of this simulation study, certain nuances of the three maneuvers should be made clear. First, the limiting factor in the constant-speed cornering maneuver is usually the amount of drive torque required to maintain constant velocity. The longitudinal slip required to produce 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 likelihood 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.

(Incidentally, it is not known if this difference in the potential for loss of control from lane changing on right and left curves has an influence on the accident record.)

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 0.3g 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 1. These results show the influence of skid number 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 $G = -6\%$. It can be seen that although curvature has a large influence on V_{CR}, it has only a small influence on V_{LOC}. Clearly, 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



Passenger Sedan
$e = 0.0156$ ft/ft
half worn tire
6% downgrade

Figure 1. Curvature and SN Effects on V_{CR}, V_{LOC}.

than 70 mph. For fully worn tires, even higher skid numbers would be needed. (In fact, as might be expected, there is almost a direct tradeoff between tire quality and surface quality; that is, a good tire on a poor surface is nearly equivalent to a poor tire on a good surface.)

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. The lane-change maneuver without braking was selected because curvature and superelevation were found to have a noticeable influence in this case (see Figure 2).

In Section 2.5.3.4, 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 which could result in loss-of-control situations at normal highway speeds. For example, as shown on Figure 2, 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.

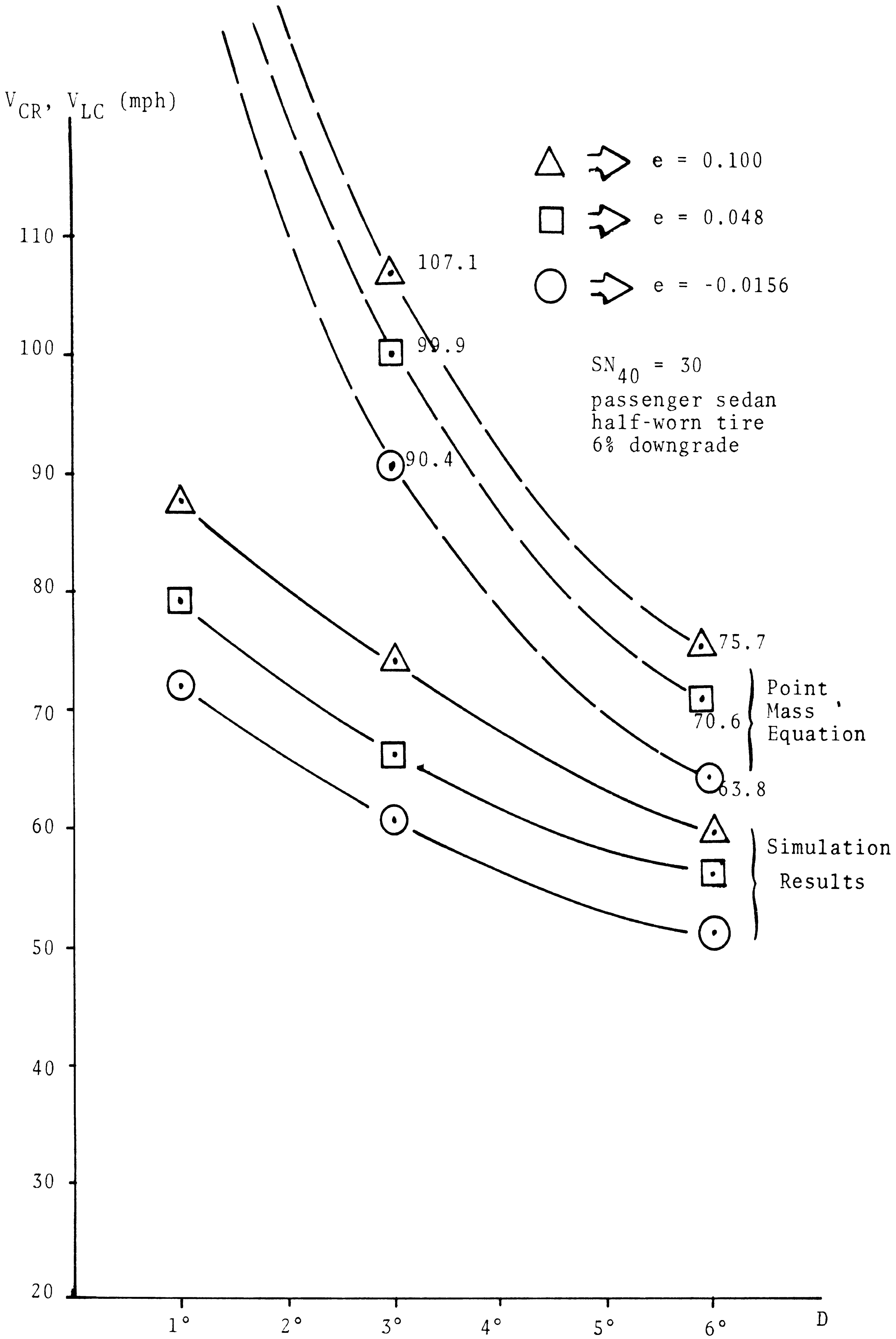


Figure 2. Effect of Superelevation on V_{LC}.

Comparable results using the simple point mass equation for cornering performance (see Equation (8) of Section 2.5.3) are also shown on Figure 2. 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.

2.3 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 occur as a result of water depths well below those needed for hydroplaning. Data obtained, for example, on a specific smooth tire (see Appendix D or (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.

Basic research on methods for predicting pavement water depth as a function of rainfall rate and pavement geometrics has been attempted 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 predicting water depth which can be written in the following form:

$$d = \left[(3.38 \times 10^{-3}) \left(\frac{1}{T}\right)^{-.11} \left(\frac{L}{e^*}\right)^{.425} (I)^{.59}\right] - T \tag{3}$$

where

d = water depth above the pavement texture, in.

T = average pavement texture depth, in.

L = pavement width, ft.

e* = pavement superelevation

I = rainfall intensity, in/hr

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

$$d = (5.9 \times 10^{-3})\left(\frac{LI}{e*}\right)^{.47}(e*^{2} + G^{2})^{.135} \qquad (4)$$

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

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

$$d = (9.6 \times 10^{-4})\left(\frac{L}{e*}\right)^{.44}(e*^{2}+G^{2})^{.045}$$

$$+ (2.26 \times 10^{-3})(I)^{.49}(e*^{2}+G^{2})^{.19} \qquad (5)$$

In examining these three formulae for predicting water depth, it can be noted that Equation (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 Equations (4) and (5), the primary geometric factors are also pavement width and superelevation. A weak dependence upon grade is indicated, while a texture term is missing. It can be concluded that road width and superelevation are the primary roadway factors affecting pavement 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 illustrated on Figure 3, which consists of a plot of water depth versus distance for separate sections of road having grades of 1% and 6%. Road width and superelevation are fixed at 24 feet and 3/16 in/ft, respectively. In comparing the three equations for predicting water depth, Figure 4 presents water depth versus road width as predicted by Equations (3), (4), and (5), for the following conditions: $I = 0.25$ in/hr, $e = \frac{3}{16}$ in. per ft. = .0156 ft/ft, and $T = 0.0117$ in. It is obvious that Equation (3) predicts much lower water depths than do Equations (4) or (5). Although the depth measurement datum for all three equations is the top of the pavement texture, Equation (3) predicts negative water depths for small roadwidths (i.e., the water level is below the top of the pavement texture), while Equation (4) predicts zero depth, and Equation (5) a positive value. These differences probably result from differences in experimental techniques used by the three

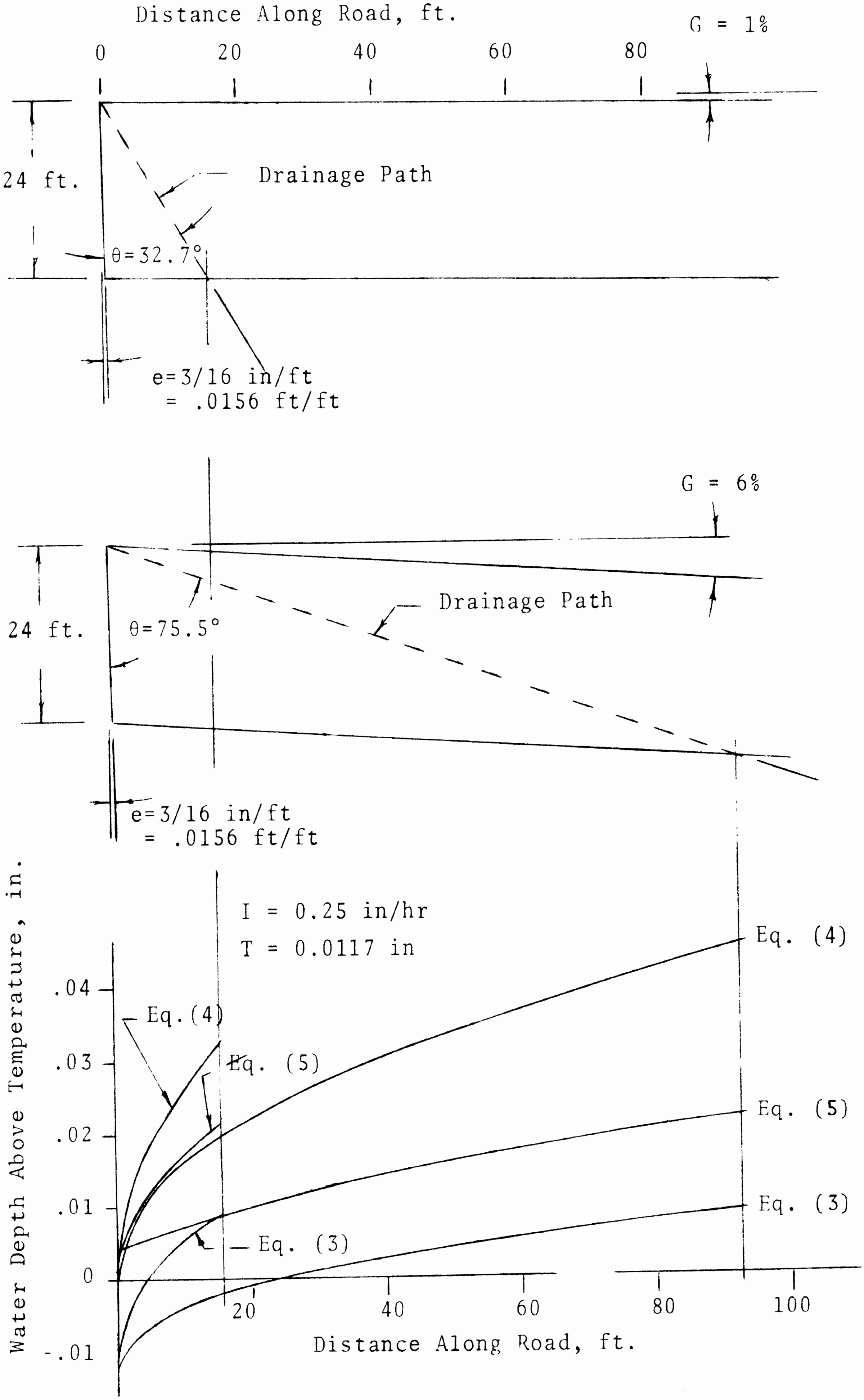


Figure 3. The Influence of Grade Upon Water Depth.

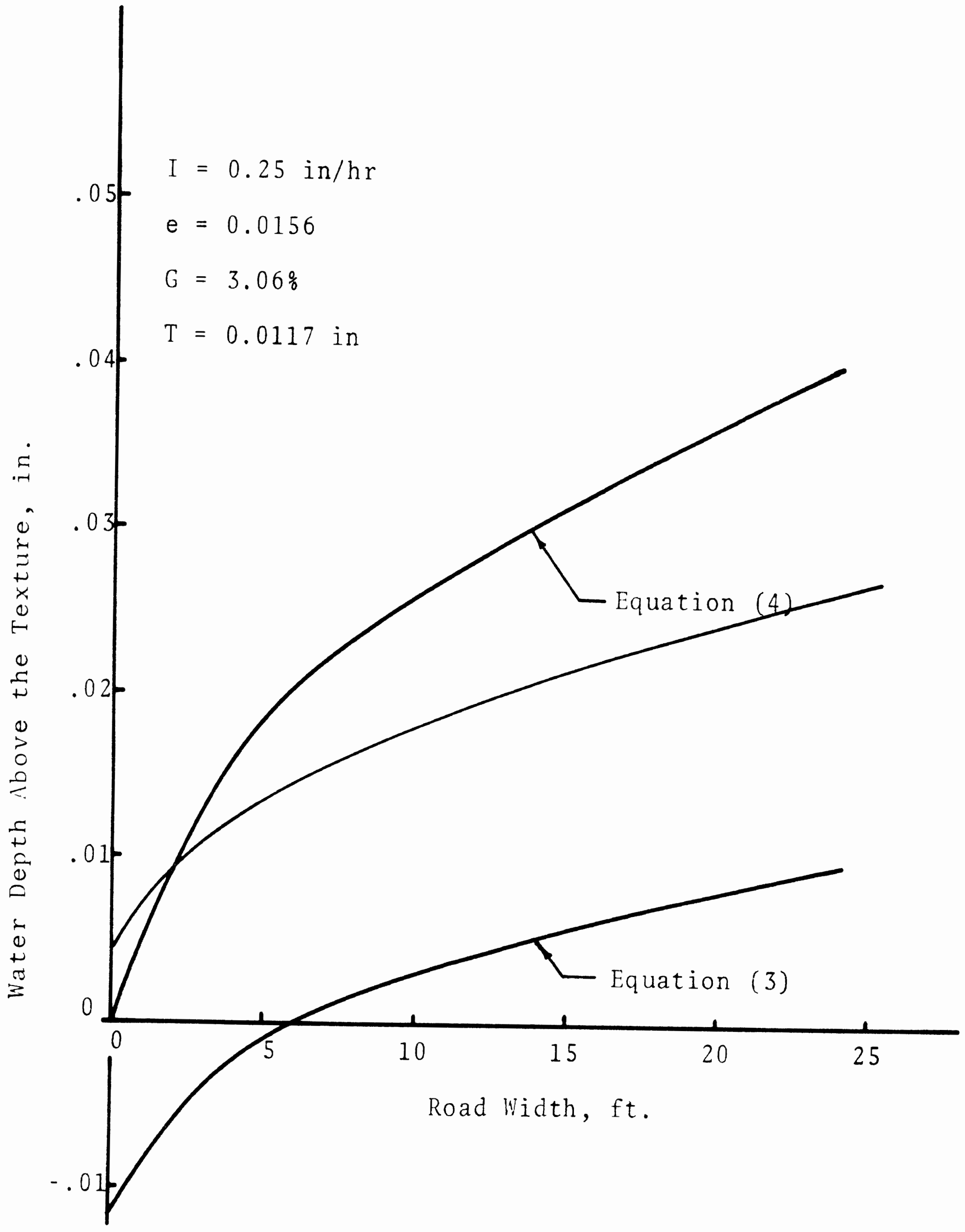


Figure 4. A Comparison of Water Depth Prediction Equations.

organizations. A second difference probably results from the fact that the pavements used in the RRL research were comparatively more coarse-textured than those used at TTI and Goodyear. Greater texture depth, according to Equation (3), should make for greater water depths. Because of these discrepancies and because of the importance of water depth on tire shear force potential, further research in the determination of water depth is recommended in Chapter 4. In discussions in later sections of this report, water depth predictions are based on Equation (4). The results, thus obtained, will lead to safer, conservative highway designs.

A demonstration of the manner in which pavement drainage influences traction is given in Table 2-12. Three types of pavement sections are compared: a tangent, a superelevated curve, and a superelevated curve plus superelevated shoulder. 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 what is available on the curves. Also shown on Table 2-12 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

TABLE 2-12

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

Pavement Section[1]	Drainage Width ft.	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 rate at 3/16" per 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.

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 somewhat 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 friction on a curve must be greater by 10 to 12 skid number units if a vehicle is to travel a curve with the same margin of safety as exists on a tangent.

In summary, pavement water depth is primarily a function of pavement width and superelevation. Grade is a secondary factor. 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.

2.4 SELECTION AND EVALUATION OF PROBLEM SITES

The 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, Virginia, where there is an interchange between I-95 and U.S. 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 which combines vertical grade with horizontal curvature. In each case, the curvature and grade are relatively gentle and well within 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 described in Appendix D. 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.

2.4.1 EVALUATION OF THE OHIO TURNPIKE SITE. The Ohio Turnpike site is a gentle one-degree curve located between Exits 10 and 11. The site lies at a point where the roadway is elevated some 60 feet above the surrounding terrain, with the grade varying between 2% and 3% downward. (See Figure D-1 of Appendix D for a plan and profile drawing of the site.) No interchange or service plaza is within three miles 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-mile segment on the Turnpike. From January 1, 1966 to May 1, 1973, a total of 55 accidents on the 0.2-mile segment were recorded. Of the total, 37 (or 67%) involved "skidding" or "loss of control" on a wet surface. Although data are not always recorded, 16 of the involved vehicles were noted 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 inch almost 70% of the time. Instantaneous *rainfall rates*, then, are probably infrequently greater than 0.25 in/hr.

Prior to June of 1970 the pavement at the site was P.C. 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 and measurements made with a British Portable Tester during this project indicate that the skid number at the site is currently between 40 and 50.

Prior to repaving, 79% of the accidents at the site occurred during wet weather. After repaving, this number decreased to 62%. These percentages are both much higher than commonly occurs along the Turnpike and, as such, indicate a definite over-involvement of wet-weather accidents.

The major cause of accidents at the site is apparently the result of inadequate pavement drainage. As was indicated in Section 2.3, 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 feet. This width includes the 24-foot width of the two traffic lanes plus a 10-foot paved shoulder, all of which are superelevated at the same rate of 3/16 in. per foot. On the crowned tangent sections of the Turnpike, the drainage width is only 12 feet, with the crown slope also being 3/16 in. per foot. The net result of the greater drainage width on the curved section located at the subject site is that water depths during wet weather are roughly twice those which occur on tangent sections.

For a rainfall rate of 0.25 in/hr, the water depth on a tangent section can be as much as 0.028 in (7). The corresponding depth at the subject site is 0.046 in. When using at least one type of full-treaded tire, the Brake Force Coefficient (BFC) for the 0.028 in. water depth is 0.26 at 80 mph. For an 0.046 in. depth, the corresponding BFC is 0.20—a difference of .06. Since BFC units when multiplied by 100 are essentially equivalent to Skid Number (SN) units, there is a loss of six SN units on the curve as compared to a tangent. For a similar tire of smooth tread, the BFC values are 0.10 and 0.04, respectively, for the tangent and curve sections. Again, a loss of six SN units is indicated, although the traction values are well below safe levels. When the traction losses due to increased water depth are coupled with the friction increment needed to travel the curve in a steady-state manner (see Table 2-12 of Section 2.3), it is clear that the friction margin available for emergency situations is substantially less for the subject curve than for a corresponding tangent section. In all, the friction available on the curve can be as much as 10 to

12 SN units below that for a tangent. With smooth tires, travel on the subject curve during wet weather appears to be extremely hazardous.

An analysis of the accident data and the above discussions indicate that the major problem at the Ohio Turnpike site is inadequate traction during wet weather. Suggested methods for improving the situation include:

1. Refusing access to the Turnpike to vehicles with smooth tires during wet weather.
2. Enforcing a reduced speed limit at the site.
3. Improving the pavement drainage.
4. Increasing the pavement friction level.

From previous discussions, the results achievable by implementing items 1 and 2 are already evident. Pavement drainage can be improved by decreasing the drainage length, 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 is not a complete solution by itself. 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, exposed aggregate (such as open graded asphalt pavement mixes), or by grooving the pavement in a transverse direction. The extent to which the situation will be improved, however, is not known, since information as to how effectively these surface treatments will improve drainage is not available. At this writing, the best suggestion seems to be to increase the surface superelevation to 0.06 by adding a wearing course of large, sharp, exposed aggregate. The superelevation increase will improve drainage, while the wearing course will improve both the drainage and the surface skid resistance. To provide for (1) the water depths that will exist even after a superelevation treatment, (2) steady-state cornering requirements, (3) a margin of skid resistance for emergency needs (see Section 2.5), and (4) a minimum tread depth of 2/32 in., it is suggested that the SN_{40} value at the identified site be kept above 65 (see Appendix D, Section D.4.3.2).

2.4.2 EVALUATION OF THE I-95 SITE. The selected site, on southbound I-95 near Fredericksburg, Virginia, consists of a curve of 1°00'56" combined with a downgrade that varies between 2.6% and 3.1%. The site is located at an interchange with U.S. 1, with I-95 passing over U.S. 1 on a bridge which is midway between the exit and entrance ramps to and from U.S.1. (See Figure D-14 of Appendix D for a plan and profile drawing of the site.)

From December 18, 1964, to June 26, 1972, 133 accidents were recorded on southbound I-95 in a region extending 1000 feet beyond the beginning and ending of the exit and entrance speed-change lanes. Of this number, 45 accidents (or 34%) involved "skidding" or "loss of control" on a wet surface. Seven percent of the total were classed as sideswipes, 26% as rear-end collisions, and 59% involved a collision with a fixed object along the roadside. Worn tires were involved in only 7% of the accidents, although tire condition was not always noted on the accident report.

The regions between the exit ramp and the bridge (approximately 1000 feet) and between the bridge and entrance ramp (also about 1000 feet), had approximately equal percentages of involvements, 27% and 24%, respectively. The same is true of the 1000-foot segments before the exit ramp (17%) and after the entrance ramp (15%). 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 were the 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 inch in 39 of the 51 wet-weather accidents. As in the case of the Ohio Turnpike site, instantaneous rainfall rates greater than 0.25 in/hr are probably infrequent.

The pavement at the site is P.C. 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 as yet. Recent skid measurements made at the site indicate that the SN_{40} value is between 45 and 60 parallel to the grooves and between 60 and 80 transverse to the grooving. (See Table D-12.)

Accident causation factors at the subject site are apparently the result of many factors which act 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 (3/16 in. per foot) as that on the Ohio site, but the drainage width is less (24 feet for I-95 as compared with 34 feet on the Ohio Turnpike). The smaller road width is due to the fact that the shoulders on the high side of the I-95 curve are not superelevated. Consequently, the maximum water depth during a rainfall of 0.25 inch per hour is 0.040 in. on I-95 as opposed to 0.046 in. in Ohio. The two sections are compared in Table 2-13 in terms of expected SN units lost due to water depth. (The values given for the I-95 site are probably somewhat pessimistic, since the beneficial effects of pavement grooving are not accounted for. Grooving aids water expulsion in the tire/road contact patch, and the longitudinal grooving at the I-95 site will be most beneficial during cornering.) Whereas traction losses due to water drainage are somewhat of a problem at the I-95 site, the situation is not as acute as seems to be the case at the Ohio site.

Site geometry and signing often combine to produce situations where 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 U.S. 1 and the city of Massaponax is completely obscured by two other signs. An exit speed advisory sign of 25 mph cannot be seen until the vehicle actually turns into the exit. The exit ramp is relatively steep (6.5% downgrade) and is sharply curved (initially 4.9° to the right and then 7.9° to the left). Considering that the exit ramp advisory speed is 25 mph,

TABLE 2-13

COMPARISON OF FRICTION LOSSES DUE TO WATER DEPTH AT I-95 AND OHIO TURNPIKE PROBLEM SITES

Site	Maximum Drainage Length	Maximum Water Depth[1]	SN Units Lost[2]		
			40 mph	70 mph	80 mph
I-95, Fredericksburg	24 ft.	0.040 in.	2	3	4
Ohio Turnpike, M.P. 166.5	34 ft.	0.046 in.	3	5	6

[1] Based on Equation (4)

[2] Based on 5.20 x 10 full treaded tire (5)

the exit deceleration lane (although longer than would be suggested by current AASHTO recommendations for the existing ramp curvature) is at least 150 feet 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 three feet of the road edge, also contribute to the loss of sight distance. Since the bridge is both on a curve and at the top of a crest (the road grade changes from -2.64% to -3.1% just south of the bridge), the road ahead cannot 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 which 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 upon the bridge.

South of the bridge, the entrance ramp and acceleration lane are difficult to see due to the road crest mentioned above, 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%) 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% along the length of the acceleration lane, the existing acceleration lane is almost 1800 feet 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 1-3 have already been discussed in Section 2.4.1 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 which obscure the exit sign—U.S. 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 which obscures the icy bridge warning sign; and (4) adding a "MERGE" message below the merge arrow just prior to the entrance lane.

It is assumed that it will not be feasible to alter the basic curve/grade geometry of the site. Nevertheless, 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 ten feet of shoulder width is available; (4) faithfully mowing the grass in advance of both the exit and entrance ramps; (5) adding raised curbs on the far side of each ramp which are painted for high visibility; 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 feet long and the entrance ramp acceleration lane about 2300 feet long.

2.4.3 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 due to 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 below.

Curvature: 1°
Downgrade: 2%
Superelevation: .0156 (3/16"/foot)
Rain
Half-worn tires on front
Fully-worn tires on rear
(Half-worn tires considered 85% effective as ASTM standard skid test tire.)
(Fully-worn tires with approximately 3/32 in. tread considered 60% effective as ASTM standard skid test tire.)
Vehicle: 1966 Ford Custom
Surface Skid Number (SN_{40}): 30
Surface Skid Number Gradient: (-.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-foot 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 5. 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.

2.5 DESIGN POLICY ANALYSIS

The formula recommended by AASHTO for curve design is:

$$e + f = \frac{V^2}{15R} \tag{6}$$

where

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

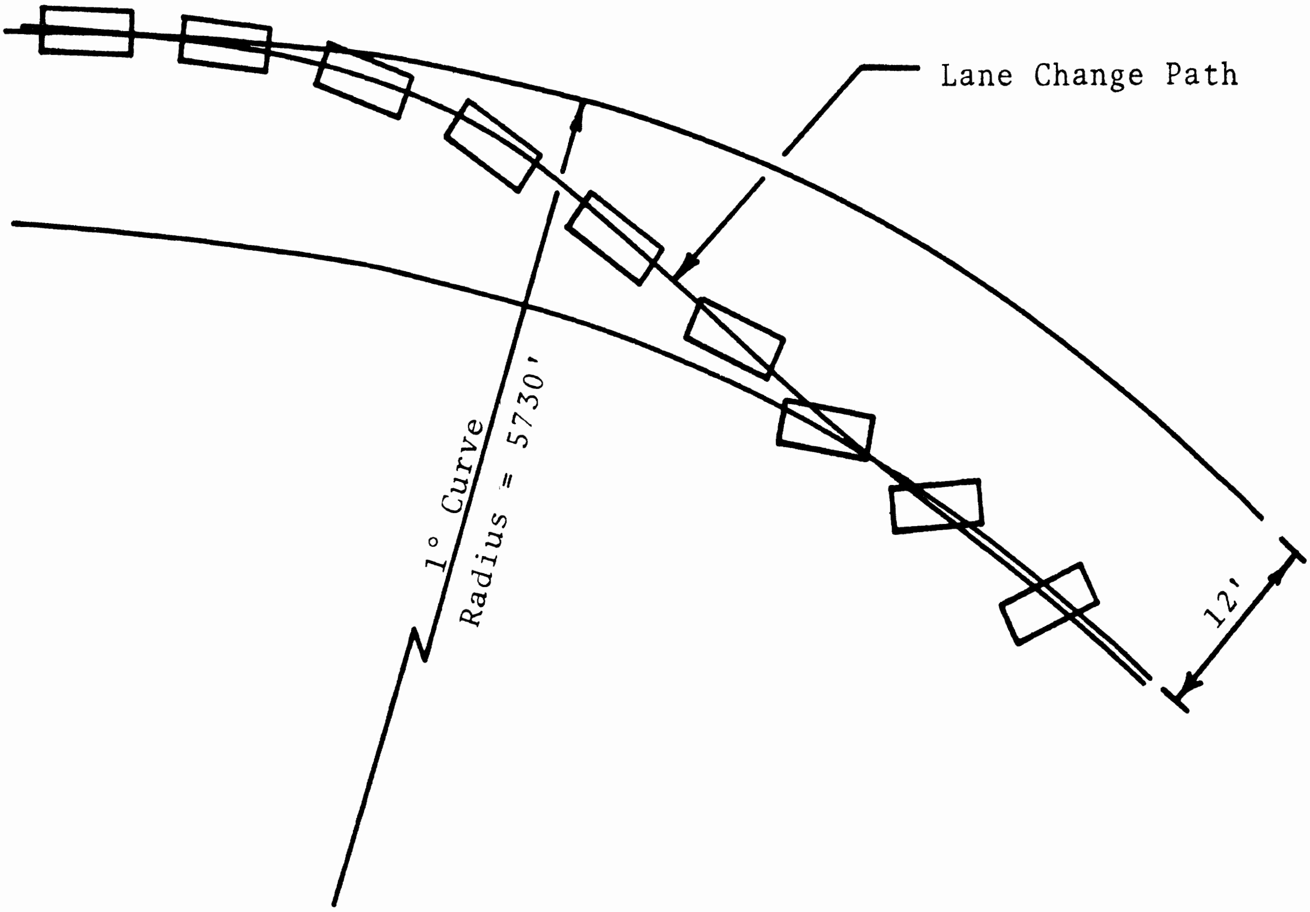


Figure 5. Accident Scenario Simulation Result.

In its present form, the formula represents a balance between the centrifugal force produced by turning and the force of gravity (e) and 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, since f represents the value of lateral acceleration 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 0.06-0.08 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.

2.5.1 SUMMARY OF FINDINGS CONCERNING A MARGIN OF SAFETY. The following discussion suggests that for roads designed in accordance with the current AASHTO design policy, an increase in skid number by an amount approximately equal to 100 times the f factor in the AASHTO design formula will allow the same side force capability for changing lanes on curves as on tangent sections of highway. Also, an increase in skid number equal to 100 times the grade in ft./ft. for downgrades will provide the friction potential for stopping in the same distance on downgrades as on level sections of road. Both the simulation findings and the analysis of accident data suggest that the margin in skid number needed to make the safety of curve/grade sites comparable to that of level tangent sections is the sum of the margin needed on curves plus the margin needed on downgrades. These ideas are expressed precisely in Equation (13).

Another skid number margin may be needed at curve sites to compensate for the loss in tire/road interface potential due to water depth. As discussed previously, the water depth at curve sites may be greater than on tangent sections of the road because the drainage path length is at least twice as long on a superelevated curve as on a crowned tangent section of roadway.

In addition to the findings concerning skid number margin, a means for estimating the skid number required to make rapid lane change maneuvers at curve or curve/grade sites is presented in Equation (9), which defines the required minimum skid number as a linear function of velocity, degree of curvature, superelevation, and state of tire wear.

In the material that follows, the curve design formula is examined for its applicability to situations involving a combined horizontal curvature and vertical grade. Next, the overall 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, in consideration of (1) and (2), the roadway skid-resistance requirements stemming from the tire/road interaction mechanism.

2.5.2 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 where

e^* = apparent superelevation

(See Appendix F for a thorough discussion and derivation of the above equation. The difference between "apparent superelevation" and "true superelevation" is also discussed in this appendix. Note that in constructing a curve on a grade, the superelevation built into the road is the apparent superelevation.)

The difference between Equations (6) and (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%. 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.

2.5.3 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 where

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

V is 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) which 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.

2.5.3.1 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 which 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," provided 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 likely 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.

2.5.3.2 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 (Section 2.2.3). 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 which 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.

2.5.3.3 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 upon the degree of curvature and superelevation, much in the same manner as V_{CR} depends upon 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 emergency 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 upon 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 cannot 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 to (1) provide as much of a safety margin for turning maneuvers as possible, and (2) maintain the friction potential of the road during rainstorms by increasing the drainage (i.e., decreasing the water depth).

2.5.3.4 The Value of the Margin of Safety for Emergency Maneuvers. Given that roads are designed in accordance with the AASHTO policy, how is the margin of safety for emergency maneuvers 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:

(1) Which tire, surface, and vehicle are to be used?

(2) Since the tire/road forces are highly dependent upon 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 skid number 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 results indicate that $SN_{40} = 40$ is the minimum skid number needed to ensure that V_{LOC} is greater than 70 mph on 3° curves for ordinary passenger vehicles with reasonably good tires. A value of SN_{40} appreciably 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 upon highway geometrics. The findings derive 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° (possibly 5°) 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:

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

where the terms are as defined before, and where

$\overline{SN}_{40}$ is the minimum allowable 40 mph skid number

D is the degree of curvature

T_F is a gross factor relating tires in use to the ASTM reference tire.

Clearly, Equation (9) is a very simple formula representing a host of complex factors. The tire factor, T_F, was taken as 1.2 for new tires, .85 for half-worn tires, and .6 for fully worn tires. The skid number gradient assumed in deriving this formula is -.5 SN per mph. For surfaces characterized by larger-magnitude skid number gradients, the formula is not conservatively safe. Also, water depth is not treated directly in this formula. Since the ASTM skid number is obtained at a water depth of approximately 0.02 inch, this equation may be applicable to weather conditions which result in about 0.02 inch 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 shear force potential. (A change in water depth of 0.01 inch can have a significant influence on tire shear force potential.) Nevertheless, this formula is useful for

(1) estimating the skid number 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 predicting an absolute value of skid number, these lane-change results can also be used to derive a skid number margin. The lateral acceleration, a_L, required to execute a lane change on a curved road derives from the superelevation and the tire/road friction potential. The frictional coupling between tire and road must be sufficient to supply the force needed to make the steady turn and to perform the lane change. The acceleration needed for the steady turn portion of this maneuver is nearly constant, since the radius of the turn is only changing about 9 to 12 feet during the lane change for typical highway curves with radii of 1000 to 6000 feet. Consequently, the maximum lateral acceleration used in a lane change can be approximated by the following expression:

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

where the terms are as defined previously, and where

a_{LC} is approximately equal to the lateral acceleration (in g's) used in a lane change maneuver on an equivalent <u>tangent</u> section of the road

Note that the term, $\frac{V_{LC}^2}{Rg}$, 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 $\overline{f}$, i.e.,

$$SN_C = SN_{V_{LC}} = 100\ \overline{f} \tag{11}$$

where SN_C equals the improved skid number on the curve at the velocity V_{LC}, and $SN_{V_{LC}}$ equals the 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 margin for downgrade sites, viz,

$$SN_G = SN_V + 100G' \qquad (12)$$

where

SN_G is the increased skid number for grade sites at a velocity V which is at or near the speed limit

SN_V is a safe skid number for level tangent sections of the road at the selected velocity, V

and G' is the magnitude of the downgrade

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

$$SN_{CG} = SN_V + 100(\overline{f} + G'') \qquad (13)$$

where the terms are as defined before, and where

SN_{CG} is the improved skid number for curve/grade sites at a velocity, V, which is at or above the speed limit

G'' is equal to the magnitude of the grade for downgrades and is equal to 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 the Ohio 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 is used in Ohio for 1° curves. 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 which have 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 moderate 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 3

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, provided that 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 which possess 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 is potentially more hazardous 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.

3.1 NEW DESIGN APPLICATIONS

The major applications to new design which have resulted from the study findings are:

1. The AASHTO design guidelines for superelevation rate should be adhered to, with the exception that restrictions should be placed on the guidelines to ensure adequate pavement drainage.
2. Road surface skid resistance should be increased on those sections of highway where operating conditions impose a greater demand for tractive forces at the tire/road interface.
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 subsections.

3.1.1 AASHTO CROSS-SECTION DESIGN POLICY.

The six sections of highway investigated in this program were designed by five different highway organizations. None of these organizations uses the superelevation rate levels recommended by the AASHTO. As examples, the superelevation rate policies for the Ohio and Pennsylvania Turnpikes, as given near the beginning of Appendix A, can be compared with the recommended AASHTO values (2) for a 70 mph or 80 mph design speed. The primary area of difference lies in the range of curves with low degree of curvature. Comparisons of recommended superelevation policies for all five highway organizations for a one-degree curve are shown on Table 3-1. 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 one-degree 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 3-1 shows comparisons for only five organizations involved in highway design, there are ample grounds for suspecting that these findings are quite typical. Lack of conformance with AASHTO recommendations for superelevation rate is probably the rule rather than the exception.

TABLE 3-1

A 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 $e_{max} = 0.12$.

The current AASHTO policies regarding drainage considerations in cross-section design are contained in Chapters 3 and 4 of Reference 2 (*A Policy On Geometric Design of Rural Highways, 1965*—referred to subsequently as GDRH), and in Chapters H and I of Reference 3 (*A Policy On Design of Urban Highways and Arterial Streets, 1973*—referred to as DUHAS). On page 162 of the GDRH, the policy regarding drainage for the "Sharpest Curve Without (i.e., not requiring) Superelevation" is restated 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 restated as:

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

On pages 349-351 of DUHAS, the policy for drainage in terms of "Cross Slope Arrangements" is stated as:

Cross Slope Arrangements

Basic Sections

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.

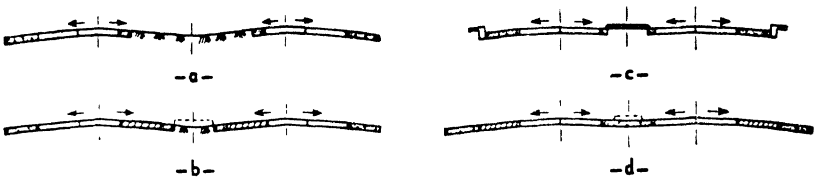
The cross slope and crown arrangement of the pavement have the very important function of draining the surface. Under certain conditions vehicles will hydroplane, i.e., the condition where one or more tires of a moving vehicle are separated from the pavement by a film of water; usually due to a combination 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.

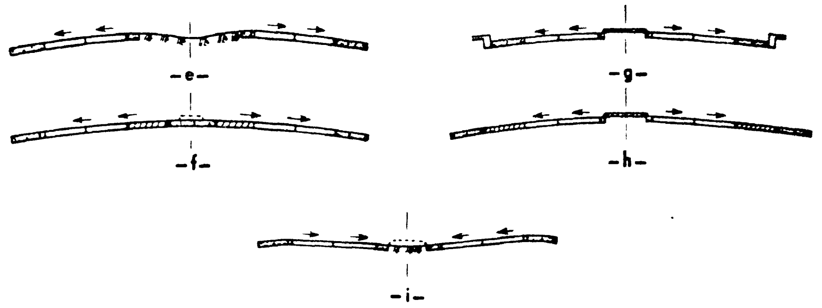
Pavement sections showing basic cross slope arrangements for divided highways are illustrated in figure H-7. In figures H-7a to H-7d, inclusive, pavements drain laterally each way from a crown line which normally is located on the centerline of each pavement. However, it may be off center initially where 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 progressively 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



EACH PAVEMENT SLOPES TWO WAYS



EACH PAVEMENT SLOPES ONE WAY

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

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 1/8 to 1/4 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

> Highway Design–Elements 351
>
> 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 1/8 inch per foot and the maximum slope in the outside lane(s) be 1/4 inch per foot.
>
> For operational reasons, the use of cross slopes steeper than 1/4 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 1/2 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:

> 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.

and on page 442, under the subject of "DESIGN ELEMENTS— Pavements and Cross Slope," policy is stated as:

> *Pavement and Cross Slope*
>
> Through traffic lanes should be at least 12 feet wide. Nonsuperelevated sections should be sloped a maximum of 1/4 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.

In summarizing the various remarks concerning satisfactory cross-slope for drainage, it can be concluded that anything between 0.008 and 0.0208 feet/foot 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, i.e., pages 349-351 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. Lanes having progressively increased slope will experience greater water depths than those which are sloped at just one maximum rate. Vehicle handling performance may be adversely affected in crossing the crown line, however, and this possibility should be examined. Crossing the crown line on a multi-lane highway (e.g., for a passing maneuver) should be of little concern, however, and remarks to this effect should appear in the AASHTO policy discussions.

3.1.2 SPECIFIC CROSS-SECTION DESIGN CONSIDERATIONS FOR DRAINAGE. From the findings reported here, it is clear that road width and superelevation are the primary factors influencing drainage on highway cross-sections. Surface texture has a lesser effect, while 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 an effective drop of six or seven skid number units in pavement skid resistance. (See Figures D-6 and D-7.) (If the water reaches a depth of 0.10 in. to 0.15 in., hydroplaning is likely and essentially all cross-sections should be designed to limit the depth of surface water to a maximum value. If it can be expected 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 road width, L, and the superelevation, e. On a curve, the road width is equal to the pavement width plus the width of paved superelevated shoulder on the high side of the curve, if one is present. As shown in Appendix C, 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 6 shows the drainage design parameter, $K(\frac{L}{e})$, plotted versus rainfall rate, as computed from Equation (4). 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 used in pavement skid testing (11). However, limiting the depth to 0.02 in. is not always practical; thus curves for other maximum design water depths are included. If a water depth design value greater than 0.02 in. is used, however, the skid resistance of the pavement should be increased to compensate. Figure 6 is therefore 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 3-2. Note that design water depths greater than 0.06 in. are not recommended since hydroplaning may occur at these depths.

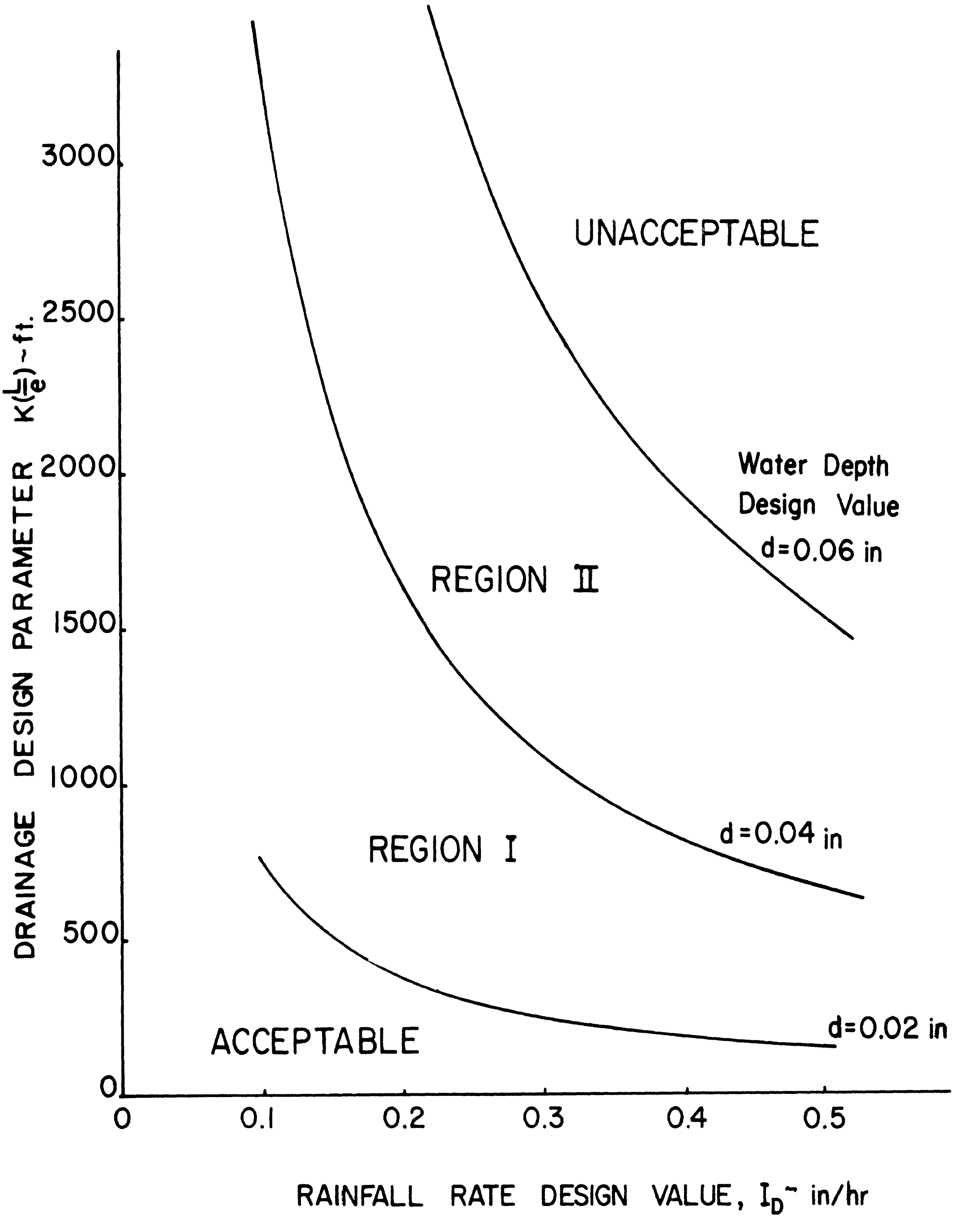


Figure 6. Drainage Considerations in Safe Cross-Section Design.

Table 3-2

Skid Resistance Increment vs. Design Water Depth

Region on Figure 6	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	0.02 - 0.06	13
Unacceptable	> 0.06	Not Recommended

In using Figure 6, a Rainfall Rate Design Value must be selected and the quantity $K(\frac{L}{e})$ must be computed. It is suggested that rainfall rates between 0.25 and 0.50 in/hr be used for design purposes, depending on local precipitation experience. Rates greater than these values are relatively uncommon, cause reduced visibility, and hence a reduction in traffic speed. (See Table D-7 of Appendix D.) The increased water depth and resulting loss in friction accompanying very high rainfall intensities is, thus, partly compensated by lower speeds and the correspondingly reduced friction demand of the traffic. Note that the parameter, $K(\frac{L}{e})$, is solely a function of the design of the cross-section. K is related to the overall slope of the surface and can be determined from Figure 7. L and e have been defined earlier.

Use of Figure 6 in designing a cross-section is illustrated by the following two examples:

Case 1 - A Curved Section

Site Characteristics:

Width of Roadway	24 feet
Width of Superelevated Shoulder:	10 feet
e	$\frac{3}{16}$ in. per ft.
G	3%
I_D	0.25 in/hr

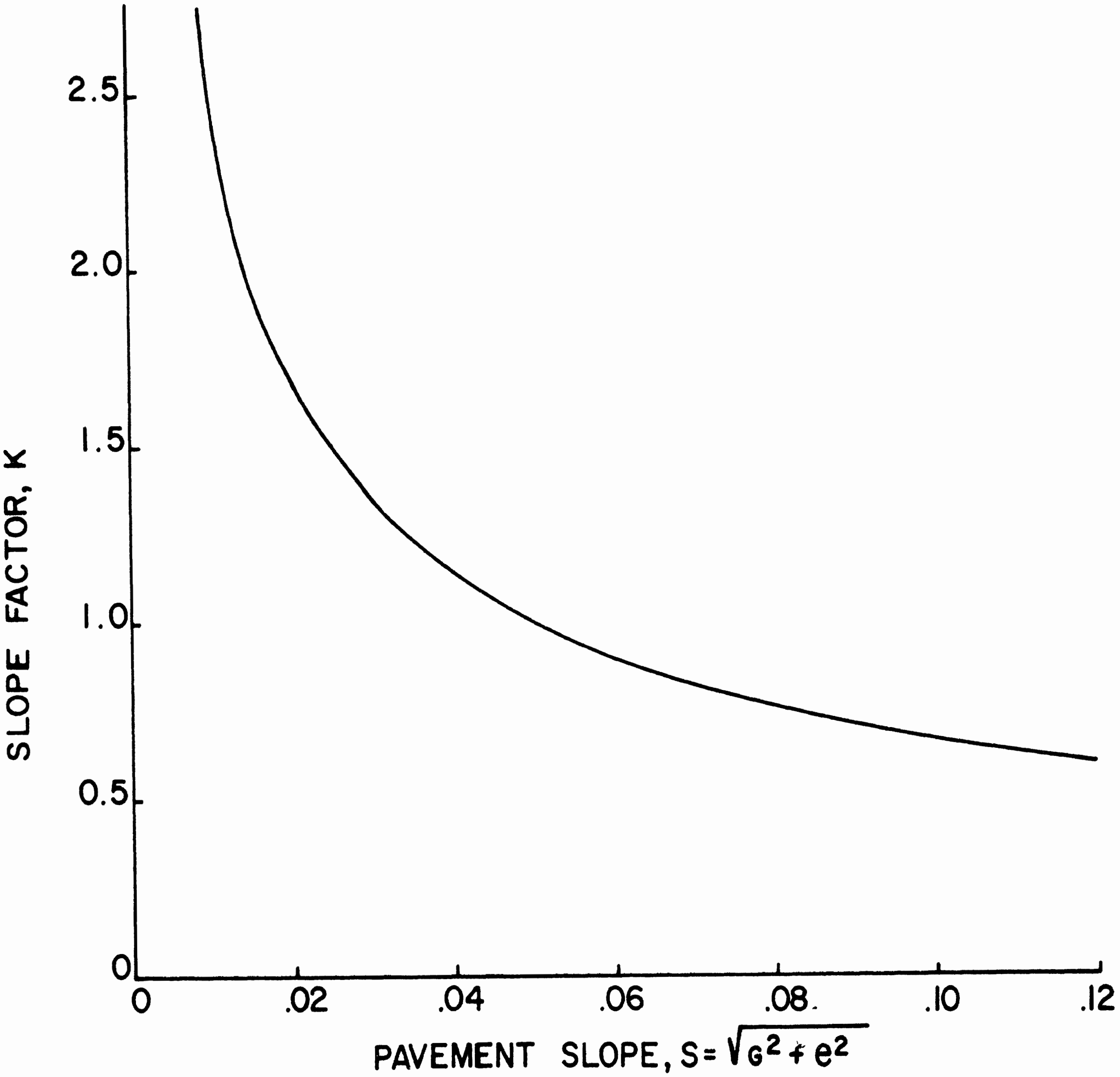


Figure 7. Slope Factor Versus Pavement Slope.

It follows that $S = 0.0338$, $K = 1.26$, $L = 30.5$ ft. (namely, the distance from edge of paved shoulder to the right-wheel path in the right lane), and $K(\frac{L}{e}) = 2460$ ft. With the assumed value of I_D and the above-calculated value of $K(\frac{L}{e})$, the design falls within Region II of Figure 6. Thus, on the basis of drainage considerations alone, the skid number at the site must be 13 SN units greater than would be required on a section where the maximum expected water depth is 0.02 in.

Case 2 - A Tangent Section

Site Characteristics:

Width of Roadway	12 feet
Width of Superelevated Shoulder	None
e	$\frac{7}{16}$ in. per ft.
G	0.0%
I_D	0.25 in/hr

It follows that $S = 0.0365$, $K = 1.20$, $L = 8.5$ feet (distance from center of crowned section to right-wheel path in right lane), and $K(\frac{L}{e}) = 280$ feet. Thus, for Case 2, the design falls in the acceptable region and no increase in skid number is indicated.

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. As indicated in Section 2.5, curvature and grade, in addition to drainage, also contribute to the need for additional skid resistance at particular sites. Practical methods for specifying these additional requirements are given in the next subsection.

3.1.3 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 Equation (13). This equation can be modified as follows to account for deficiencies in pavement drainage and for the influence of tire characteristics different from that of the ASTM standard tire:

$$SN_{CG} = \frac{SN_V + 100(\bar{f} + G) + SN_D}{T_F} \qquad (14)$$

where SN_D is the skid number increment from Table 3-1, and where other terms have been defined previously.

Equation (14) can be further modified to yield an expression for the required skid number at 40 mph. The result is:

$$SN_{40CG} = \frac{SN_{40T} + 100(\overline{f} + G'') + SN_D}{T_F} + SN_{grad}(V-40)\left(\frac{1-T_F}{T_F}\right) \tag{15}$$

where newly used terms are defined as follows:

SN_{40T} = the SN_{40} value needed on a tangent section

$\overline{f}$ = $\frac{V^2D}{85,944} - e$

SN_{grad} = the skid number gradient, SN/mph (Note that SN_{grad} is almost always negative)

V = a characteristic velocity which is 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, mph.

Values of T_F for use with the equation 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_{40CG} which 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 which are characteristics of legal minimums in most states are given in Table 3-3 (12).

Table 3-3

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

Values of SN_{40T} should be selected to reflect safe driving experience on tangent sections. An acceptable value can be determined from Figure 1. For example, the SN_{40} value needed to safely carry out a lane change and braking maneuver on a tangent section with a vehicle using half-worn tires (T_F = .85) is about 40. (See the V_{LOC} curves on Figure 1 for velocities near 80 mph.) A value of 40 for half-worn tires translates to an SN_{40} value of 34 (= 40 x .85) for a standard ASTM test tire.

In summary, Equation (15) provides a means for determining pavement skid resistance requirements for curve and curve/grade sites. This equation is based on (1) the skid resistance required for safe maneuvering on tangent sections; (2) additional increments in skid resistance to compensate for curvature and grade; (3) pavement surface drainage factors; and (4) a tire tread-wear factor.

Examples of the use of Equation (15) to specify frictional requirements are as follows:

Case 1 - Curved Section of Pavement with Moderate Superelevation

Site Characteristics:

Width of Roadway	24 feet
Width of Superelevated Shoulder	10 feet

D	1°
e	$\frac{3}{8}$ in. per ft.
G	3%
V	80 mph
I_D	0.25 in/hr
Tire Tread Depth	$\frac{2}{32}$ in.

Derived Quantities:

S	0.0372
K	1.19
L	30.5 feet
$K(\frac{L}{e})$	1,160 feet
SN_D (Region I)	7
$\bar{f}$	.043
SN_{grad} (Assumed)	-0.5 SN units/mph
T_F	0.50

Substituting the above derived quantities into Equation (15) yields

$$SN_{40CG} = \frac{34 + 100(.043 + .030) + 7}{.50} - (.5)(40)(\frac{1-.5}{.5}) = 76$$

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 76. If the tires have full tread depth (T_F = 1.2), the corresponding value is 43.

Case 2 - Curved Section of Pavement with Large Superelevation

Site Characteristics:

Same as Case 1, except that

e	$\frac{3}{4}$ in per ft
Width of Superelevated Shoulder	None

Derived Quantities:

S	.0693
K	0.83
L	20.5 feet
$K(\frac{L}{e})$	272 feet
SN_D	0
$\bar{f}$	.012
SN_{grad}	-0.5 SN units/mph
T_F	.50

Substituting the above derived quantities into Equation (15) yields a required SN_{40} value of 50. Thus, by doubling the superelevation and shortening the drainage length, the required skid number has been reduced from 76 to 50. Again, for fully treaded tires, the required SN_{40} value is 33. Thus, if the skid resistance were made adequate for a 2/32 in. tread, a margin of 17 SN units would be available when fully treaded tires are used.

Equation (15) 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.

3.1.4 MANEUVER CONSIDERATIONS IN ROADWAY DESIGN.

Equally important to providing adequate skid resistance is the necessity for reducing the demand for emergency maneuvering at a site. The main factors that influence the need for emergency 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 design guidelines that do exist, such as those in AASHTO geometric design manuals (2, 3) and the Manual on Uniform Traffic Control Devices (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:

1. the cues which 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.

3.2 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 check list. 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 are provided with two columns on the right-hand side which 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 4

CONCLUSIONS AND SUGGESTED RESEARCH

4.1 CONCLUSIONS

The findings from the accident data analyses, simulation studies, and field site investigations performed in this study can be integrated to develop tentative guidelines and design policy recommendations which will create the margins of safety needed to facilitate controllable and safe maneuvers on highway sections with combined vertical and horizontal alignment.

In this study no evidence was found to indicate that geometric effects due to curvature and grade combine to produce a more dangerous situation than that produced by grade and curvature taken individually. Consequently, separate skid number increments have been recommended to compensate for the loss in acceleration capability required for performing (1) stopping maneuvers on downgrades and (2) lane-change maneuvers on curves. In addition, another increment in skid number has been proposed to alleviate loss-of-control problems occurring at curve sites characterized by large road widths and/or low superelevations.

It appears that there are no basic problems (other than the problems that exist for flat curves) with use of the AASHTO design formula, as recommended for level, horizontal curves, to design highway geometrics for curves on grades. However, it is recommended that superelevation levels at the upper end of the AASHTO specified values be used to (1) provide as much of a margin of safety for turning maneuvers as possible, and (2) maintain the friction potential of the road by limiting water depth during rainstorms. (This recommendation applies to all curves, including curves on grades and curves on the level.)

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 shows no statistically significant dependence of the accident rate on grade or curvature except that <u>a specific 1° curve on a 3% downgrade has a very high accident rate</u>.
2. The accident rate on the Pennsylvania Turnpike does not depend upon grade but it does increase significantly with increasing side friction factor. (Side friction factor is the component of centripetal acceleration provided by the tire/road interface in a steady turn maneuver.)
3. The accident history at the 1°-curve, 3%-downgrade site in Ohio, identified as being highly over-involved in the production of accidents,

appears to be highly associated with wet pavement and worn tires.

4. A lane-change maneuver, shown to be a critical condition at curve sites, could result in loss of control situations at normal highway speeds for passenger vehicles with half-worn tires operating on surfaces with $SN_{40} = 30$.

5. The analytical and simulation work performed in this study showed grade to be a roadway factor of small influence.

6. In a limited simulation study, emergency maneuvering of a motor vehicle was found to be a more likely cause of loss of control than external disturbances, such as road bumps and simple wind gusts.

7. The lane change and braking maneuver used in this study was severe enough that grade and curvature had only a small influence on the maximum speed at which this maneuver could be performed without loss of control.

8. Highway sites having combined curvature and grade were found to require greater pavement skid resistance as an emergency-maneuver safety margin than corresponding tangent sections.

9. Pavement drainage was shown to be an important consideration at curve sites, and the ratio of total road width to superelevation was found to cause unfavorable water depths on some 1° curves.

10. Methods for evaluating problem sites were developed and used to conclude that (1) a drainage problem exists at the problem site selected on the Ohio Turnpike; and (2) many factors, including drainage, short speed-change lanes, insufficient sight distance, and obstructed signs contribute to the high accident rate at the problem site located on I-95 near Fredericksburg, Virginia.

In general, the program consisted of three major activities: (1) accident data analysis; (2) computer simulation; and (3) field site investigation. These activities were integrated to provide a multifaceted approach in which each activity contributed useful findings which could be compared and verified in the other activities. This multifaceted approach is recommended for use in other research endeavors concerned with safety problems involving the highway-vehicle-driver system.

4.2 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 3. 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 to reduce 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 (1) resolve the differences in the findings of earlier studies (6-9); (2) determine tire longitudinal and lateral force characteristics as a function of controlled water depth and tire wear; and (3) develop means for measuring average water depth on highways during rainstorms.

3. More field investigations of problem sites should be made to see if site difficulties can be identified at a number of curve and curve/grade sites, using the site investigation methodology developed in this program.

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. More simulation studies should be made to investigate other maneuvers which might cause loss-of-control problems and the potential for skidding on highways. 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.