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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT 68

~~APPLICATION OF~~ VEHICLE OPERATING CHARACTERISTICS ~~TO GEOMETRIC DESIGN AND TRAFFIC CONDITIONS~~

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT 68

APPLICATION OF VEHICLE OPERATING CHARACTERISTICS TO GEOMETRIC DESIGN AND TRAFFIC CONDITIONS

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RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION
OF STATE HIGHWAY OFFICIALS IN COOPERATION
WITH THE BUREAU OF PUBLIC ROADS

SUBJECT CLASSIFICATION
- HIGHWAY DESIGN
- HIGHWAY SAFETY
- ROAD USER CHARACTERISTICS
- TRAFFIC CONTROL AND OPERATIONS

HIGHWAY RESEARCH BOARD
DIVISION OF ENGINEERING NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING 1969

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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

In recognition of these needs, the highway administrators of the American Association of State Highway Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Bureau of Public Roads, United States Department of Transportation.

The Highway Research Board of the National Academy of Sciences-National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

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

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

This report is one of a series of reports issued from a continuing research program conducted under a three-way agreement entered into in June 1962 by and among the National Academy of Sciences-National Research Council, the American Association of State Highway Officials, and the U. S. Bureau of Public Roads. Individual fiscal agreements are executed annually by the Academy-Research Council, the Bureau of Public Roads, and participating state highway departments, members of the American Association of State Highway Officials.

This report was prepared by the contracting research agency. It has been reviewed by the appropriate Advisory Panel for clarity, documentation, and fulfillment of the contract. It has been accepted by the Highway Research Board and published in the interest of an effectual dissemination of findings and their application in the formulation of policies, procedures, and practices in the subject problem area.

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FOREWORD

By Staff

Highway Research Board

This report will be of interest to traffic engineers, highway design engineers, automobile designers, and other officials responsible for the safety aspects of the nation's highways and the motor vehicles that use these highways. This investigation involves the compatibility of the operating characteristics of motor vehicles with highway design and traffic operation procedures currently in use. Major reference books used by highway designers and traffic engineers were reviewed to determine where present practices might be affected by changing vehicle characteristics. Suggestions are made for improved highway design and traffic operation techniques. Also included is a listing of suggested research needs.

Highway design criteria and traffic operation procedures are currently based on rational mathematical extensions of vehicle design and operating characteristics, such as acceleration rates, braking ability, and vehicle size and weight. In order to make these mathematical extensions, it is necessary to make many arbitrary assumptions involving design speed, reaction time, sight distance, and various other parameters. One problem is that vehicle characteristics change over a period of years, but the highway plant in the United States, consisting of more than three million miles of roads and streets, changes very slowly.

A need has been expressed to update vehicle performance data for the purpose of updating design criteria and traffic operations procedures. However, before this is done, it is necessary to determine which design criteria and traffic operations procedures really need to be, or should be, based on vehicle characteristics, and identify the important vehicle characteristics that are not presently known. It was with these thoughts in mind that this project was initiated in January 1966. From the initiation of this project it was anticipated that additional research would be necessary to quantify certain present and future vehicle characteristics, but this quantification was not considered to be within the scope of the current project.

The Cornell Aeronautical Laboratory research team has determined which highway design criteria and traffic operations procedures require a knowledge of motor vehicle characteristics. Current sources of information were reviewed to determine what data are currently available involving vehicle characteristics. Characteristics that need to be quantified for vehicles now on the road, as well as for future vehicles, have been identified. By reviewing the elements of geometric design and traffic operations presented in the basic design and policy manuals, the researchers have determined how vehicle characteristics are being utilized. A rational approach was used to determine, expand, or modify the existing design and operations criteria. The research has revealed those vehicle characteristics which should be known and used for highway design and traffic operations.

A program of future research is included to quantify the relationships between various vehicle characteristics and highway design and traffic operations procedures. Recommended studies involve superelevation, lane width, transition curves, tire coefficient of friction, vehicle handling quality, field of vision, and headlight sight distance.

CONTENTS

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The research reported herein was performed under NCHRP Project 3-10 by the Cornell Aeronautical Laboratory with Morton I. Weinberg, Head, Transportation Systems Section, as Principal Investigator. Other Cornell Aeronautical Laboratory staff personnel working on the portions of the project reported herein were as follows:

Kenneth J. Tharp, Principal Systems Engineer, who performed the literature research for and wrote the section on geometric design and traffic control procedures; Harvey Goldstein, Associate Electronics Engineer, and Richard A. Raub, Operations Analyst, who assisted in the literature survey; and Kenneth Perchonok, Associate Statistician, who wrote the appendix on statistical sample sizes and measuring accuracy.

Appreciation is expressed to the following individuals who provided the project team with valuable assistance:

D. W. Loutzenheiser, W. A. Walker, A. Taragin, S. C. Tignor, and S. R. Byington, of the Bureau of Public Roads; and K. A. Stonex, General Motors Corporation.

APPLICATION OF VEHICLE OPERATING CHARACTERISTICS TO GEOMETRIC DESIGN AND TRAFFIC CONDITIONS

SUMMARY

The information contained in this report will be useful to agencies responsible for highway design and traffic operations in revising standards and procedures with a view toward their modification and/or modernization.

Five nationally used reference books for highway design and traffic operations procedures have been reviewed, along with three typical state highway manuals. The objective of the review was to determine where practice might be affected by vehicle characteristics, particularly as these characteristics change with successive designs or are performance capabilities that are modified by driver preference.

No standards or procedures were found to exist in which changes appeared to be mandatory because of changes in vehicles. Practically all of the recommendations that have been made for reconsideration and review, or establishment of new standards, derive from increased technical knowledge concerning the relationship of the vehicle to the highway and to traffic operations. Statistically derived probabilities of occurrences are the foundations for other recommendations. An example of the first kind is taking into account field of vision from the vehicle when determining clearance of obstacles as a factor in lane-width requirements. An example of the second kind is to determine the relative likelihood and consequences of skidding on a curve with superelevation, either when the vehicle is stopped on an icy surface or skids on that surface as a result of excessive centrifugal force.

Driver-modified performance capabilities of vehicles lead to still other recommendations. Typical examples are: taking into account body-roll angle when determining minimum radius of curvature of a horizontal curve by the ball-bank indicator method, and the setting of the length of the amber phase of a traffic signal, as a function of approach speed.

One philosophical point is made. Necessarily, the highway system endures longer than the vehicles that use it. Economic constraints, then, require that some standards be imposed on vehicle manufacturers so that those characteristics that have a strong interaction with highway design will be stabilized for significant periods of time. Highway designers can ill afford a fluctuating policy on design standards that tries to maintain compatibility between the highway and an autonomous vehicle-manufacturing industry. Such standardization might apply to location and aiming of headlights, rear-light configuration and intensity, height of the drivers' eyes, downvision angle over the nose, and underclearance and end clearance.

The accompanying table, included to serve as a quick reference for highway designers and administrators, summarizes the findings resulting from the research, particularly as applied to highway geometrics.

SUMMARY OF RESEARCH FINDINGS AND RECOMMENDATIONS AS APPLIED TO HIGHWAY GEOMETRICS

SUBJECT	EXISTING CRITERIA SATISFACTORY	RECOMMENDATIONS
Sight distance:		
Stopping	Yes	No recommendations are made for change or improvement.
Passing	—[a]	It is doubtful whether any significant improvement can be made in the existing method. At present, research is being conducted which will provide improved knowledge of it.
Headlight	—[a]	Simplest method would probably be a graphic solution as shown in Appendix A.
Speed adjustment	Yes	No recommendation.
Horizontal alignment:		
Max. curvature (high speed)	No	Use of the angle obtained from the ball-bank indicator. Further studies would be advisable.
Max. curvature (low speed) transition curves	Yes	No recommendations are made.
Transition curves	Yes	The use of spirals is urged in preference to compound curves.
Profile:		
Grade	Yes	
Vertical curves	Yes	
Cross section:		
Number of lanes	Yes	
Cross slopes	Yes	Improvement on the guides for establishing maximum cross slopes might be obtained from more comprehensive studies of the effect of lateral slopes upon vehicles at various speeds.
Superelevation	—[a]	The present method of selecting maximum superelevation needs review.
Superelevation runoff	—[a]	Additional work might be undertaken to qualify reasonable limiting values of roll rotation of vehicles for use in the selection of superelevation runoff length.
Lane width	—[a]	Lane width should take into account more vehicle characteristics than the present policy.
Median and median openings	—[a]	Additional attention should be given to the possibility of better headlight glare screening, improved safety, and easing of driver tensions.
Shoulders	—[a]	Improvements in shoulder design could be made by considering the probability of vehicle failure, the traffic volume, and speed of traffic flow, the probability of an accident occurring, the cost of such an accident, and the cost of constructing the shoulder.
Curbs	—[a]	The need for curbs should be thoroughly investigated.
Roadside	—[a]	The knowledge of safety aspects resulting from lateral slopes, placement of structures, aesthetic considerations must be included in the selection of the roadside feature.
Auxiliary lanes and areas: Speed change lanes	—[a]	No recommendations are indicated.
Truck passing lanes	Yes	No recommendations are indicated.
Left-turn lanes	Yes	No modification.
Weaving section	Yes	No recommendation.
Parking facilities	Yes	Standards must continue to reflect the physical size and turning radii of vehicles.
Traffic guidance and protective devices:		
Channelization	—[a]	Consideration of vehicle characteristics which are part of the design of lane width, curve radii, curb height, visibility, etc.
Guide posts	—[a]	The use of guide posts as barriers is a mistake, and the use of guardrails is urged whenever containment is desired.
Guardrails	—[a]	There is need for extensive research on the design and placement of guardrails.
Running speed	No	The present practice of reducing the quality of design by limiting special facilities to accommodate only those vehicles traveling at the lower running speed should be eliminated.
		Field of vision, deceleration capability vs speed, and coefficient of friction vs speed in the AASHO Policy are valid and no change is warranted.

[a] A determination as to whether the existing criteria are satisfactory cannot be made without consideration of other factors.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

This report deals with the problem of determining the functional relationship of the general class of on-highway vehicles to highway design geometry and to traffic control and operational procedures. The task of discerning and describing these functional interactions was performed as Project 3-10 of the National Cooperative Highway Research Program.

Cognizance of the need for reasonable compatibility between vehicles and the surfaces over which they move stretches back into antiquity.

As this problem of compatibility between the highway and the vehicle has approached modern times, other considerations—such as traffic regulation and control, and passenger convenience and comfort—have emerged. But it should be noted that in a rigorous sense there is no need for regulation and control, comfort and convenience. These are arbitrary factors, stipulated only because our modern technology and affluence make them reasonably attainable.

The enduring nature of the highway and the temporal character of the modern passenger car have served as one of the bases in this investigation. This report points up those characteristics of the vehicle, the highway, and traffic operations for which reasonable compatibility should be assured.

In the problem statement and research objectives that apply to this project it is noted that ". . . it is necessary to determine (a) the design criteria and traffic operations procedures that really need to or should be based on vehicle characteristics, and (b) the vehicle characteristics that are not sufficiently known at the present time to satisfy these requirements."

The project has been divided into three principal tasks, each of which is reported separately in the technical sections that follow. The first task was a literature search. A list was made of documents that are nationally (and internationally) recognized as authoritative for both design of highway geometrics and traffic operations procedures. Each of these, manual, policy, or handbook, was reviewed thoroughly and a notation was made of every design or procedural item on which a vehicle physical or functional characteristic had a direct, or indirect, bearing or interaction. Where numerical criteria have been given, these have been set down either individually, or the range of values has been shown. Tabulations and graphs are noted, but not reproduced. Included in the list of documents were three representative state highway department design manuals. A compilation of the pertinent findings in all of the documents comprises a section of Chapter Two. Commentary has been added where it is deemed to be of value. Recommendations for revised procedures are made when they seemed to be appropriate.

The second principal task is reported in another section of Chapter Two. All design and operating characteristics of vehicles, from a "macroscopic" point of view, that interact with the highway design and traffic operations procedures, are listed and discussed. In reviewing these characteristics, some note has been taken of present design practice; comments are made on some methods used to determine numerical values for the characteristics. For others, new methods are suggested for acquiring these numerical values. The section includes a treatment of what the vehicles of the future may bring that can affect present design standards and operating procedures.

A third section of Chapter Two is devoted to detailed discussions of additional considerations that are thought to be appropriate to some geometric standards and operating procedures. Suggestions for new design standards are made (as contrasted with arriving at new values to be applied to existing design policies). In addition to arguing the need for the standard, methods are given for obtaining the values to implement the standard, whether it derives strictly from the vehicle or from the vehicle-driver combination. Chapter Two also indicates where the most complete files of information on vehicle characteristics are to be found, and the nature of the data.

Chapter Three contains a commentary on the findings, on the generality of their practical application, and the action (and classification of action) that might be followed in moving to implement the findings. Also, it is indicated that some of the burden of standardization of the highway transportation system must be borne by vehicle manufacturers.

Chapter Four deals with conclusions and suggested research. In this chapter, the recommended action items are listed and discussed in a summary fashion. The most detailed "technical" treatments, on any topic, are found in sections of Chapter Two.

The appendices include treatments of technical areas for which the degree of detail presented is felt to be appropriate to the objectives of this project.

This report, generally, does not make specific recommendations as to numerical solutions, where deficiencies are believed to exist in highway design standards or traffic operating procedures. This constraint derives from literal translation of the wording of the project statement, and meticulous care has been taken to treat only the highway geometrics, traffic operation procedures, and vehicle characteristics. Where vehicle performance capabilities are modified by drivers, this has been shown. Where deficiencies are believed to exist, methods for finding solutions are suggested in some cases. Throughout, it has been assumed that the prerogatives for design changes will rest with the responsible highway designers.

CHAPTER TWO

FINDINGS

The following is largely a review of important and widely known and accepted documents on highway design and traffic control procedures. These are:

1. *A Policy on Geometric Design of Rural Highways.* Published by the American Association of State Highway Officials (1965).
2. *A Policy on Arterial Highways in Urban Areas.* Published by the American Association of State Highway Officials (1957).
3. *Highway Capacity Manual.* Published by the Highway Research Board as *Special Report 87* (1965).
4. *Manual on Uniform Traffic Control Devices for Streets and Highways.* Published by the Bureau of Public Roads (1961).
5. *Traffic Engineering Handbook.* Published by the Institute of Traffic Engineers (1965).

In addition, three state highway design manuals, selected at random as typical, are included. They are:

6. *Planning Manual, Part 7—Design.* Published by the California Division of Highways (1963).
7. *Geometric Highway Design Standards.* Published by the Connecticut Highway Department (1961).
8. *Highway Survey and Design Manual.* Published by the Michigan State Highway Department (1960).

The discussions in the first section are summary in nature: no specific references are made to the documents listed.

GEOMETRIC DESIGN AND TRAFFIC CONTROL PROCEDURES

Geometric Design

The geometric design of a highway is the visible layout of the facility, and consists of such elements as the number of lanes, lane width, horizontal and vertical alignment, shoulders, side slopes, etc. Each element is selected or designed after consideration of many diverse factors. In the following discussion, the geometric elements are listed, briefly defined, and certain design considerations are recorded. The major emphasis has been placed upon those considerations which are related to the vehicle in some manner. In the many instances where the design of an element is dependent upon one or more other elements, these elements are listed and reference to their discussion is given. Design considerations unrelated to the vehicle, such as aesthetics and drainage, are mentioned if they play a major part in the design of an element. Also, the extremely important factors of economic considerations are outside the objective of the present study and therefore are not mentioned as design criteria.

Major Design Controls

The recommended procedure for determining highway design criteria and warrants involves giving the facility a designation consisting of the major controls or services for which the highway is to be used. The following are the major controls as recommended in *A Policy on Arterial Highways in Urban Areas:*

ADT, current and future years (the average daily traffic); DHV (the design hour volume); D (the directional distribution of DHV expressed as a percentage of the major one-way flow to total flow); T (the number of trucks, exclusive of light delivery trucks, expressed as a percentage of DHV); V (the design speed); and C of A (the degree of access control).

The major design controls—ADT, DHV, D, and T—relate to the amount and type of traffic that will use the facility. Estimates of these values for the design time period are obtained from predictions based on observations of present and past traffic volumes, trip generation characteristics, etc.

The design speed is "A speed selected for purposes of design and correlation of those features of a highway, such as curvature, super elevation, and sight distance, upon which the safe operation of vehicles is dependent" (*Highway Capacity Manual, 1965*), or "The highest sustained speed under conditions of low traffic volume, good road surface, and good weather that individual vehicles can travel with safety" (*Traffic Engineering Handbook*).

The design speed of a particular highway is selected after due consideration of the topography, the type of area (open, built up), and economic considerations. Normal ranges of design speeds have been from 30 mph in urban areas to 80 mph in open, comparatively flat terrain. Observations of highway traffic have indicated that these limits are reasonable for the foreseeable future and therefore the present policy tends to stay within this range.

Control of access refers to a public authority limiting, preventing, or in some manner controlling direct access between the road and the abutting property. The major benefit of such control results from restricting the number of traffic disturbances caused by vehicles entering or exiting the roadway. Without access control, entrances and exit facilities will be built at various and often numerous locations along the roadway. Each of these entrance and exit facilities causes disturbances in the traffic flow and results in decreased capacity and greater traffic hazards.

The major design controls are an indication of the traffic volume, level of service and type of service for which the facility is to be designed. Volume demands and driver desires are the most important consideration in establishing these controls. The specific level of service is the goal of geometric design. Although the various vehicle characteristics indirectly affect the selection of the major design controls, these characteristics will more properly be considered within the elements of geometric design and within the procedures of traffic operation.

Sight Distance

Stopping

Stopping sight distance is the total distance traveled by a vehicle from the instant the need to stop is visible to the driver until the vehicle actually stops. The distance traveled during the time required for driver perception, decision-making, and reaction is included as well as the actual braking distance. The time delay distance is speed times the time delay as obtained from conservative interpretation of statistical observation of human behavior. Braking distance is a function of brake efficiency, tire-to-road surface friction, vehicle speed, and the gradient of the roadway. The relationship (neglecting gradient) may be expressed as

$$S = \frac{V^2}{30\,(f + g)} \qquad (1)$$

in which:

$S =$ braking distance
$V =$ vehicle speed, mph
$g =$ braking efficiency or friction coefficient, whichever is lower
$f =$ percent of grade

Controlling stopping distances (that is, the maximum length stopping distances) occur on wet pavements where the coefficient of friction is low and the running speed is assumed to be less than the design speed.

The design method recognizes that trucks, especially the larger and heavier ones, require longer stopping distances than passenger cars for which the method is developed. This longer distance is assumed to be offset by the higher seating position of the driver, an advantage if the sight restriction is over the crest of a hill, and by the somewhat lower running speeds of trucks.

The method of obtaining stopping sight distances incorporates the visibility from the driver's seat in the vehicle and the braking characteristics of the vehicle-road combination. With the present-day vehicle these two items appear to be the only vehicle characteristics which would affect stopping sight distances. Therefore, no recommendations are made for the change or improvement of the method used for calculating the minimum sight distance.

Passing

Passing sight distances are calculated from observations of traffic patterns which were recorded in the years 1938 to 1941 and partially restudied in 1957. The method involves the summation of four distances:

d_1—the distance that the passing vehicle travels while the driver observes and decides to pass and then accelerates his vehicle. The distance extends to the point at which the passing vehicle encroaches upon the left lane. The appropriate equation is:

$$d_1 = 1.47t\,(v - m + at/2) \qquad (2)$$

in which:

$t =$ time of the initial maneuver, seconds
$v =$ speed of passing vehicle, mph
$m =$ difference in speed between passed and passing vehicles, mph
$a =$ average acceleration of the passing vehicle, mphps.

d_2—the distance traveled by the passing vehicle while in the left lane, measured from the point where the vehicle first entered the left lane to the point where it returns to the right lane. The value may be calculated as:

$$d_2 = 1.47t \qquad (3)$$

in which

$t =$ time in left lane, sec

The speed of the passing vehicle is assumed to be 10 mph faster than that of the passed vehicle.

d_3—a safe distance between oncoming traffic and the passing vehicle at the time that the passing vehicle returns to the right-hand lane. The values used are statistical averages of the data recorded in the original study. The distances are proportional to speed.

d_4—the distance traveled by oncoming traffic during the period of time starting from the point-of-no-return of the passing vehicle to the right lane (blocked by passed vehicle) and ending when the passing vehicle has returned to the right lane. The assigned values are equal to $\frac{2}{3}d_2$ and are based upon approaching vehicles traveling at the same speed as the passing vehicle and on the assumption that the passing vehicle can return to the right lane behind the passed car during the first one-third of the time in the left lane.

The previously mentioned studies obtained statistical values for the various times, speeds, accelerations, and distances necessary for use in determining the various *d* values.

The accepted method of calculating passing sight distances makes use of vehicle acceleration (as monitored by the driver) and certain visibility characteristics of the vehicle (special consideration to right rear view). The AASHO *Policy* mentions the consequences of passing on grades where the weight-power ratios of the vehicles involved would possibly produce different conclusions, although no definite recommendations are advocated for these cases.

Passing sight distance is basically a statistical quantity measured from actual driver behavior. Because the drivers are going to have the final word in the decision on whether to pass or not to pass, it is doubtful whether any significant improvement can be made in the existing method; that is, the drivers require a period of time for observing, thinking, and reacting; accelerate at a preferred level; and leave some minimum distances between opposing traffic. Any method of calculating passing sight distance is going to rely upon a statistical evaluation of these driver responses as observed in field studies.

At present, research is being conducted which will provide improved knowledge of the passing maneuver. Initial reports on this research indicate that, if the passing driver was informed of the speed of the oncoming cars, the passing maneuver would be improved (*1, 2*).

Headlight

Headlight sight distance is the length of roadway in front of the vehicle that is illuminated by the vehicle's headlights. On straight level segments of highway, this becomes a direct function of the lamp characteristics and the aiming of the beam. On horizontal curves, the illuminated roadway is a function of lamp characteristics (including lateral dispersion) and curve radius (see Appendix A).

On hill crests, the illuminated roadway extends from the vehicle to a point where the light rays become tangent to the roadway, assuming that lamp characteristics are not a limiting factor. Beyond the point of tangency, only those objects which project into the lights' rays are illuminated. The horizontal distance from the vehicle to point of tangency can be easily calculated from the height of the lamp and the properties of the highway profile—similarly, the distance from point of tangency to a protruding object also can be determined.

On sags in the highway profile, headlight sight distance may be restricted because the light rays being emitted from the lamps on a downgrade will tend to shine into the pavement on the ensuing uphill grade. The calculation of the distance of effective illumination may be otained by headlamp location above the road surface, the upward dispersion of the beam, and the properties of the profile.

The calculated headlight sight distance on hill crests and sags is a function of the height and aiming of the lamp as well as certain lamp characteristics (light intensity and dispersion).

Other than these items, it appears that there is no vehicle factor that would appreciably contribute to headlight sight distances—unless loading effects could be quantified, somewhat as done in the SAE *Handbook*.

The 1965 AASHO *Policy on Geometric Design* states: "Since the design speed of most turning roadways is governed by the horizontal curvature and since the curvature is relatively sharp, a headlight beam parallel to the longitudinal axis of the vehicle ceases to be a control." If the desire is to be able to see the roadway ahead of the vehicle, headlight illumination on horizontal curves might be considered because length of the illuminated roadway will vary directly with curve radius. The headlamp characteristics and its aiming can easily be used to calculate sight distance on horizontal curvature, although the simplest method would probably be a graphic solution as shown in Appendix A.

Switching from high beam to low beam would affect headlight sight distance, especially in sags. The present method of determining the length of the illuminated roadway uses constant parameters and thus does not allow for this change. Simple changes in the parameters would allow for any desired headlight position and aiming.

Speed Adjustment

Speed adjustment sight distances should exist at intersections, or at other points of confliction, of lightly traveled roadways which are not controlled by signals, stop signs, or yield signs. The function of the sight distance is to allow drivers to observe opposing traffic, decide whether a conflict or collision is imminent, decide what course of action to take, take this action, and allow sufficient distance for vehicle response; that is, provide adequate distance for driver to decide to adjust speed and to do so.

Vehicle characteristics considered are the acceleration or deceleration capabilities of the vehicles, and certain driver visibility characteristics.

No recommendations or modifications are made for the calculation of speed adjustment sight distances.

General Considerations

Sight distances, as discussed and defined for geometric design, are minimum lengths of roadway. One may readily question whether these distances are the desired quantities in all instances. There is need for additional knowledge in areas such as:

1. The relationship between the driver's preferred speed and the sight distance ahead. Does a driver slow down when the distance ahead becomes insufficient for him to make easy and comfortable changes in speed and lateral location although he still has far above minimum stopping sight requirements? Does a driver need confirmation of a consistent roadway design for some given distance in front of his vehicle?

2. Do high-speed stops require a different consideration than friction? Is the stopping distance more dependent upon maintaining vehicle control than upon frictional forces?

Horizontal Alignment

Maximum Curvature, High Speed

On the higher-speed roadways, the major design criterion of a curve is the countering of the centrifugal force developed when the vehicle moves in a circular path. For this criterion, the minimum radius of curvature (R) can be obtained with basic laws of mechanics as a function of vehicle speed (V mph), roadway superelevation (e in./in.), and a suitable coefficient of side friction (f). The function in simplified form is:

$$R = \frac{V^2}{15\,(e + f)} \tag{4}$$

In the selection of curve radius, certain vehicle characteristics are considered indirectly because the parameters speed, superelevation, and the coefficient of friction (lateral force factor) involve the same vehicle characteristics. The coefficient of friction parameter is a measure of the driver's interpretation of the desired lateral force and incorporates the handling and riding qualities of his vehicle more directly than is indicated by the term.

A ball-bank indicator frequently is used to evaluate curves for the establishment of appropriate advisory speed limits. The indicator measures an angle which the resultant force makes with the reference axis of the sprung mass of the vehicle, as in Figure 1. The resulting forces, therefore, are somewhat larger than the angle the resultant makes with the normal to the road surface. Agreeable ball-bank indicator angles are 14° for 20 mph, 12° for 25 to 30 mph, and 10° for speeds as high as 60 mph. The values obtained from the ball-bank indicator would be a better representation of vehicle characteristics, as monitored by the vehicle operator, than the coefficient of friction.

Another weakness of the present method is the failure to take into account the tendency of the vehicle to overturn on a curve. The low center of gravity and comparative wide wheel base of passenger cars neutralize this effect for these vehicles. However, for trucks, the centers of gravity are at greater heights and the center of gravity height-to-wheel-base ratio may be such that overturning might be considered.

Vehicle characteristics should play a more important part in the selection of curve radii. The use of the angle obtained from the ball-bank indicator would be a more direct measure of the lateral forces which the driver will accept with a particular vehicle suspension system.

The proposed method also allows for measurement of the roll characteristics of the vehicle. The roll angle may play an important part in the control of the vehicle as some researchers indicate that this angle is what the driver instinctively measures to control his rate of turn. Further studies would be advisable in this respect.

Limiting radii also should take into account the possibility of a commercial vehicle with a high center of gravity overturning on a curve.

Maximum Curvature, Low Speed

On low-speed facilities where the centrifugal forces are negligible, the minimum radius of curve or turn is determined by the turning and tracking characteristics of the design vehicle selected for that particular road. The minimum radius of the roadway should be sufficiently large so that all of the wheels of the design vehicle follow the prescribed path without encroaching upon adjacent areas. The entire turning maneuver should be possible in a single forward movement of the vehicle.

The minimum radius for low-speed turns is based directly upon the turning and tracking characteristics of the design vehicle.

No modifications or recommendations are made.

Transition Curves

Transition curves often are used to provide gradual change from a tangent to a curve or from one radius of curve to another. Their functions are:

1. To provide gradual changes in radial acceleration and vehicle directional control.
2. To provide suitable distances for superelevation runoff.
3. To provide distance for changes in pavement width.
4. To improve the aesthetics.

Transition curves are of two general types: a spiral which allows the change to be uniformly distributed over a length of roadway, and a compound curve which provides a step change.

The general highway spiral is developed from the desired relationship that the radius of curve at any point on the spiral is inversely proportional to the distance along the spiral. The theory of the spiral may be found in several route surveying textbooks. The design of a spiral for a particular condition is the selection of an acceptable spiral length. One method of selection is based upon attaining radial acceleration at a uniform and agreeable rate. In the simplest form, this selection is expressed in the equation:

$$L_s = \frac{3.16V^3}{R_c C} \quad (5)$$

in which

L_s = length of spiral, ft
V = speed, mph
R_c = radius of curve, ft
C = rate of increase of radial acceleration, ft/sec²/sec

The value of C was originally established as 1 for railroad curves (*4*). For highway design, higher values of C are acceptable and values ranging from 1 through 4 have been used. Within limits, the selection of C is the prerogative of the designer.

A second method of establishing spiral length is to make the spiral of sufficient length for the change between the normal crown section and the superelevation runon and runoff. This method involves the rotation of the vehicle about a longitudinal axis and is regulated by limiting the difference in grade between the pavement center line grade and the pavement edge. For example, a 2 percent rotational change in cross slope per sec would indicate a need of 3 sec to obtain a superelevation of 0.06 ft per ft, and at a speed of 40 mph this would require a spiral length of approximately 175 ft.

In addition to establishing a spiral length for comfort, a maximum rate of rotation is also important from aesthetic considerations. If the pavement rotates too quickly, it presents an unpleasing appearance. The limitation is accomplished by establishing the maximum ratio of the grade of the pavement edge to the grade of the center line. These ratios vary with design speeds.

Compound curves are restricted by the ratio of the radius of the flatter curve to the radius of the sharper curve. A ratio of 1.5 is believed to be the maximum value for the open highway and a ratio of 2 appears to be permissible on slow-speed facilities.

The principle of the transition curve is to allow the vehicle driver to ease his vehicle into a change of path without sudden changes in his driving procedure and riding com-

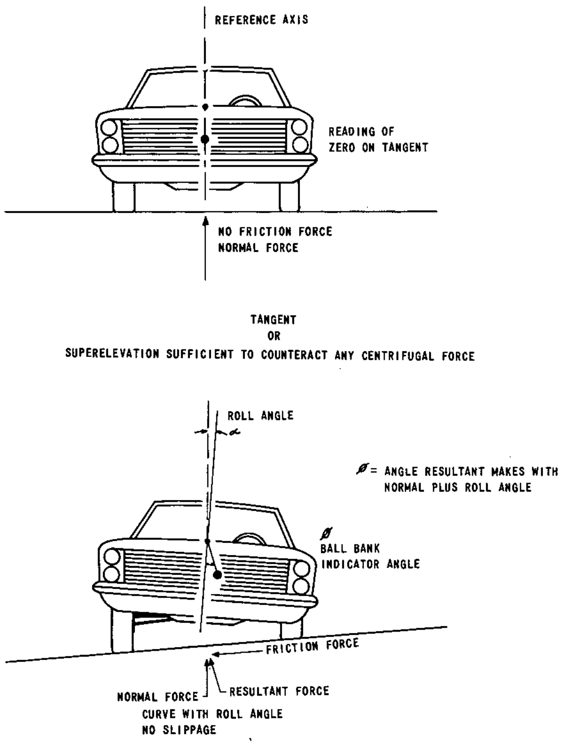


Figure 1. Ball-bank indications on curves.

fort. The method of design of the spiral assumes that the directional change should be spread uniformly over a distance. Assuming uniform vehicle speed this also means a uniform time distribution of directional change. There is no evidence to indicate that the method does not adequately allow for vehicle characteristics.

The use of compound curves to approximate a uniform change by a step increase in curvature does not match vehicle and driver characteristics as neatly as the spiral. In traveling through a compound curve the driver-vehicle system will smooth out the change into a more nearly uniform variation.

There is no recommendation for changing or modifying the spiral concept of transition curve. The use of spirals is urged in preference to compound curves.

The acceptable, or non-objectionable, rates of longitudinal rotation could be investigated. The present values appear to be rule-of-thumb estimates without any derived backing.

General Considerations

Broken-back curves and reverse curves are considered as poor design practices and therefore should be avoided whenever possible. The difficulties encountered are too many and too quick changes in superelevation, in radial acceleration, and in the adjustment of vehicle directional control.

Another consideration in the design of curves is to maintain desired sight distances for both daytime and night driving. In horizontal alignment, daytime sight distances are generally controlled by obstacles located at the side of the road or in the immediate vicinity: for example, a building located near a corner may interfere with the line of sight connecting intersecting streets. At night the headlight sight distance may be a controlling factor. A judicious selection of curve radii may provide more desirable sight distances.

Profile

Grades

The steepness and length of grades affect traffic by causing reductions in the operating speeds of the vehicles using the facility. Speed reductions are most evident in the vehicles having low power-to-weight ratios; for example, trucks are not capable of maintaining high speeds up grades. Thus, maximum gradients and critical grade lengths are calculated as those upon which a loaded truck can operate without an unreasonable reduction in speed. Other factors of consideration are topography, area development, etc. Minimum gradients, if necessary, are controlled by the requirements for drainage and construction techniques.

The selection of maximum gradient and length of grades requires consideration of vehicle operating characteristics on inclines. The basic problems concern the prevention of excessive losses in highway capacity, the minimization of the reduction in speed, and, in general, more nearly optimize the operating conditions and level of service of the facility. Each particular design of a grade involves a balance of the highway operation desired versus the requirements of topography, type of area, construction techniques, etc.

The method of selecting gradient and length of grade utilizes vehicle characteristics to a considerable degree and the method serves the desired purpose.

Vertical Curves

Vertical curves, the transition zones between different gradients, are designed with consideration given to the factors of tolerable or comfortable rates of change in grade, adequate sight distance for stopping, and passing, and a pleasing appearance. When there are extreme changes in grades or grade changes are accomplished in very short distances, underclearance of the vehicle must be considered.

Selection of vertical curve length on the basis of the rate of change of gradient results in controlling the vertical radial acceleration of the vehicle. The appropriate form of equation used for calculating vertical curve length is:

$$L = \frac{(1.47v)^2\,(g_1 - g_2)}{100a} \tag{6}$$

in which

L = length of vertical curve, ft
v = speed, mph
g_1 = approach grade, percent
g_2 = departure grade, percent
a = vertical radial acceleration, ft/sec^2

Satisfactory limits on vertical radial acceleration are dependent upon many vehicle characteristics, suspension system, weight, tires, etc. For design, past experience has indicated that the rate of change is satisfactory if vertical radial acceleration is approximately 0.5 ft/sec^2 for high-class roads and a maximum 1.5 ft/sec^2 for low-class roads. Only in rare circumstances does the vertical acceleration govern the length of a vertical curve.

Sight distance is the major consideration and normally the control in the design of a vertical curve because changes in grades, especially from an upgrade to a downgrade, result in sight restrictions. When going over a crest, a motorist's forward vision is limited by the sharpness of the crest (a long vertical curve will reduce the sharpness), the height of the driver's eyes above the pavement, and the height of the object to be viewed. Present policy places the eye at 3.75 ft above the pavement and the object height at either 6 in. for stopping sight distance or at 4 ft for passing sight distance. The sight distance can be expressed as a function of the two intersecting grades, the length of the vertical curve, and the heights used.

Sag vertical curves, downgrade to upgrade, are not subject to sight restrictions during daytime driving. At night, sag vertical curves should provide adequate headlight sight distances. The method of calculating this distance is given in the AASHO *Policy*, 1965.

Changes in elevation in extremely short distances, such as from pavement level to sidewalk in a few feet (a driveway entrance), may result in other critical controls of design. In these limiting circumstances, the vehicle may drag or scrape as it passes over the quick change. The physical dimensions (wheelbase, overhang, underclearance) of the vehicle are the controlling factors. Two suggested methods of preventing dragging are (1) no more than a 5 percent change in grade between successive 10-ft chords, and (2) no more than 1.5 in. of clearance between the pavement and a 10-ft straight edge.

The methods used for design of transition areas between different grades reflect several vehicle characteristics through sight distance and physical clearances. The methods of calculation are satisfactory.

Cross Section

Number of Lanes

The number of lanes is dependent upon the anticipated volumes of traffic which have been predicted for the facility when operating at the desired level of service.

Vehicle characteristics are considered in the selection of the number of lanes through the capacity and level of service of the highway.

No changes or revisions are recommended.

Cross Slope

Lateral slopes on the roadway are desirable for drainage. Minimum lateral slopes are dependent upon the drainage characteristics of the surface and, to a lesser degree, upon the construction techniques employed. Excessive crowns or lateral slopes on the traveled portion of the roadway are driving hazards because vehicles tend to veer toward the low edge and lateral skidding can occur.

Maximum lateral slopes are obtained by consideration of vehicle handling characteristics. In general, the minimum slope that will provide adequate drainage on the roadway is used, provided this slope is within the limits that are considered acceptable for vehicle operation. Cross slopes up to ¼ in. per ft are barely perceptible, as far as their effect on steering is concerned. Cross slopes of ¼ to 1 in. per ft require a conscious effort in steering and increase the proneness to lateral skidding.

Improvement on the guides for establishing maximum cross slopes might be obtained from more comprehensive studies of the effect of lateral slopes upon vehicles at various speeds. The present limitations appear to be used because they have proved satisfactory in operation.

Superelevation.—Superelevation is the tilting, or banking, of the traveled portion of the roadway so as to counteract part or all of the centrifugal force developed when a vehicle travels a curved path. Maximum rates of superelevation are derived either from the limiting lateral coefficient of friction of stopped or slow moving vehicles on slick (icy) surfaces, or from the consideration of comfort of vehicle operation.

The one criterion of maximum superelevation considers the limiting coefficient of lateral friction under adverse weather conditions and is therefore a direct measurement of this characteristic. The other criterion is derived from subjectively interpreted radial acceleration comfort limit, and as such becomes a statistical evaluation of driver preference.

The present method of selecting maximum superelevation needs review.

Superelevation Runoff.—Superelevation runoff is the length of the roadway which allows the change from a normal cross section to a superelevated cross section, or vice versa. The runoff should occur over a sufficient length of roadway to result in a pleasing appearance and also to provide comfortable and safe operation. To ensure comfortable vehicle operation, the rate of rotation of the vehicle about a longitudinal axis must be limited. The common design procedure is to restrict the relative difference in gradients between the pavement edges to a specified value according to the number of lanes and design speed and thereby prevent excessive rates of roll rotation.

Length of pavement for superelevation runoff is based upon vehicle rate of longitudinal rotation.

Additional work might be undertaken to quantify reasonable limiting values of longitudinal rotation of vehicles for use in the selection of superelevation runoff length.

Lane Width

On tangent segments and comparatively flat curves, the minimum lane width has been determined by summing what is deemed a safe and observed lateral clearance between opposing vehicles, the clearance between the vehicle and the pavement edge, and the width of the vehicle. The data used to establish lane width were published in 1944 (*5*).

On turning roadways, recommended lane width provides for the off-tracking of the vehicle's rear wheels and front and rear-body overhang, as well as the necessary vehicle width and clearance from both sides of the lane.

Lane-width selection is indirectly influenced by many vehicle characteristics as modified or interpreted by the driver. The data from which acceptable lane width has been determined indicated that, with a 12-ft lane width, commercial vehicles, when passing in opposing directions, tend to leave 3 ft between the left wheel and the center line and 3 ft between the right wheel and the pavement edge. However, with a truck width of 8.5 ft (design vehicle), it is difficult to leave 3 ft on each side of the vehicle on a 12-ft lane. Passenger-car observations indicated a similar split of the lane at an approximate 11½-ft lane width. Indications were that wider lane width provided unused areas of pavement. The study concluded that an 11-ft-wide lane would be preferred for passenger vehicles only, and a 12-ft lane is needed for commercial or mixed traffic.

The observations placed a measure on the lateral clearance distances which drivers felt as being satisfactory for their vehicle. Less widths are believed to cause emotional strain and thus reduce the capacity and safety of the highway.

The 12-ft lane width was originally established for use on 2-lane highways. This width has subsequently been carried over to use on multilane facilities where the operating conditions are somewhat different.

The determination of lane width for turning roadways is affected by vehicle characteristics to a larger degree, particularly the off-tracking of long vehicles.

Lane width should take into account more vehicle characteristics than does the present policy. Although Taragin's procedure (*5*) took into account the handling characteristics of the vehicle, the determination was based only on clearances between vehicles moving in opposite directions. It is possible that the overtaking maneuver may require consideration, a point that is discussed subsequently.

Medians and Median Openings

Medians separate opposing streams of traffic. The width of the median is closely related to economics and the available right-of-way. One major function of the median is to provide an area for a driver to regain control of his vehicle after running off the pavement. As such, the median should be adequately wide and free from obstructions. Other functions are to reduce headlight glare, to provide space for turning movements, occasionally to be a haven during emergencies, and to serve as a pedestrian refuge.

Openings in medians should be of sufficient length and radius to allow the permitted movements to be accomplished without difficulty.

The width of medians is recognized as being important to safety and driver comfort. There have been studies which indicate that some 50 to 60 ft (*6, 7, 8*) are desirable widths for safety. Greater widths provide further minor reductions in head-on collisions. However, in many situations, the width is governed by factors other than safety and comfort; for example, the cost of the additional right-of-way which is required for wide medians may be extremely high.

Median openings serve a specific vehicle need and therefore are designed for the particular design vehicle under consideration. Length of opening, radius of turns, etc., are taken from tabulated vehicle requirements.

The selection of median width depends on a few vehicle characteristics. Additional attention should be given to the possibility of better headlight glare screening, improved safety (by better knowledge of paths of vehicles running off the roadway, reduction in obstacles, etc.), and easing of driver tensions.

Shoulders

The basic function of shoulders is to provide an escape area for disabled vehicles outside of the normal stream of traffic. Adequate shoulders also serve to provide a better lateral distribution of traffic, provide a recovery area for vehicles which run off the pavement, and aid in design for lateral support for the pavement and drainage—factors which are not traffic-related.

The recommended shoulder width for high-quality roads is that which allows movement of individuals around a stalled or stopped vehicle. If 8 ft is allowed for the width of vehicle and a 2-ft-wide work area between the vehicle and the pavement, a minimum shoulder width of 10 ft is obtained. Narrow shoulders (4 to 6 ft) encourage drivers to utilize the full pavement width but do not provide an adequate refuge area.

To perform satisfactorily, the shoulder must be surfaced so that vehicles using the shoulder may do so without danger or trouble. Sufficient lateral slopes are required for drainage and these may be steeper than the normal crown because of infrequent use and low speeds of use.

Improvements in shoulder design could be made by considering the probability of vehicle failure, the traffic volume, the speed of traffic flow, the probability of an accident occurring, the cost of such an accident, and the cost of constructing the shoulder. In other words, the economic benefits obtained from increased safety could be used to justify the construction of adequate shoulders.

Curbs

Curbs may be designed to serve several functions, some traffic-oriented and some not. The non-traffic-oriented curb functions are the control of drainage, lateral support of pavement, and certain esthetic considerations such as a finished appearance and a positive separation between roadway and adjacent lands.

Traffic-oriented functions range from the delineation of the highway, through a restraining of vehicle movements, to absolute prevention of undesirable movements. Curbs may also be classified into two types—"mountable" or "barrier." Mountable curbs are designed so that they may be easily crossed by a vehicle and therefore serve vehicular traffic as delineating or restraining devices. Barrier curbs are designed to prevent vehicular crossing and thereby apply positive restraints to certain undesired movements.

The height and steepness of mountable curbs are selected so that vehicles may cross them easily. Low curbs (3 to 4 in.) may be vertical while higher curbs require a slope to enable the wheels to mount the curb without a severe jolt to the vehicle. If parallel parking is allowed, curb height should allow clearance of the vehicle's door when opened.

Barrier curbs are designed with a steep side slope which does not allow the wheel to climb the curb and are of sufficient height so that the wheel will not roll over the curb. Good design practice calls for a curb sufficiently high to prevent a vehicle that strikes the curb within the expected angle of obliquity from rolling or tipping over the top of the barrier.

The need for curbs should be thoroughly investigated before including them in construction. Contrary to popular opinion, a 6-in.-high vehicle curb does not serve as a barrier curb and may be crossed by a standard passenger car. However, a 6-in. curb does act as an obstruction along the roadway and may be sufficient to cause a driver to lose all control of his vehicle during an erratic movement. Studies should be conducted into the advisability of using rumble strips or corrugated pavements in the places where curbs are often utilized, such as medians, dividers, traffic islands, etc.

Various stylings of barrier curbs have been proposed for use along the traveled roadway. Evaluation of these should be made before use. For instance, research personnel on this project are aware of a meritorious design of barrier curb that has not been adopted widely. Also, research into the location of barrier curbs should be undertaken to assure that the curbs are less damage-invoking than the feature from which the vehicles are being protected.

Roadside

The roadside is defined as that area of excavation or fill extending from the outside edge of the shoulder to the existing ground. Included are ditches used for longitudinal drainage, the major consideration in ditch design being whether the cross-sectional area is sufficient to carry the estimated precipitation runoff. The lateral slopes, including ditch sides, are designed to provide some amount of safe maneuver area, allow easy maintenance, and be of reasonable construction cost.

Some consideration—often minimal—is given to vehicle characteristics in the design of the roadside. More often, construction and right-of-way costs govern the design of the roadside without regard to the conditions best suited to the driver and his vehicle.

It should be emphasized that the knowledge of safety aspects resulting from lateral slopes, placement of structures (culvert headwalls, light poles, etc.), aesthetic considerations (trees in particular), etc., must be included in the selection of the roadside feature.

Auxiliary Lanes and Areas

Speed-Change Lanes

Acceleration lanes are speed-change lanes which provide a distance for vehicles entering a through stream of traffic to accelerate to the speed of that stream prior to entering it. Deceleration lanes provide a distance for vehicles to slow down after leaving the through stream of traffic and before reaching a slower-speed roadway segment. By definition, the length of these lanes has to be sufficient to allow vehicles enough distance to make the necessary speed changes comfortably. Thus, the lengths of speed-change lanes are functions of entering speed, exiting speed, and an acceptable rate of speed change.

The width of speed-change lanes is the same as that of through lanes.

A taper is commonly used at the start of deceleration lanes and at the end of acceleration lanes. The length of the taper should be approximately the distance which drivers would require to shift lanes. The data obtained during a 1941 study (*9, 10*) were interpreted to indicate that 3½ sec was an appropriate time period for a lateral shift of one lane. The length of taper is therefore taken as distance traveled in 3½ sec at the average running speed.

Speed-change lanes are specialized geometric elements which serve particular functions. As such, these elements can be and are designed for certain vehicle or driver-modified characteristics.

The method of design reflects vehicle characteristics as required for a specialized feature. The use of average running speed as a design criterion should be investigated because its use lowers the standard of design.

No recommendations for modification of design methods are indicated.

Truck-Passing Lanes

Truck-passing lanes are constructed on those grades which are too steep and/or too long for low power-to-weight ratio vehicles to maintain a satisfactory speed. The passing lanes start at the points where truck speeds become unsatisfactory and end where trucks can resume a satisfactory speed. Passing-lane width is the same as that of normal lanes. End tapers may be selected in the same way as they would be as for acceleration and deceleration lanes.

Passing lanes are specialized geometric features and therefore are designed for particular vehicle characteristics which may be obtained from observation of vehicles on the highway.

Present practices and standards appear to be adequate. It is not expected that power-to-weight ratios will change enough to permit elimination of such lanes.

Left-Turn Lanes

Left-turn lanes are used to allow vehicles whose drivers want to turn left to be removed from the through traffic stream. The length of the lane should be adequate to store a certain number of vehicles and is thus a function of vehicle length and clear space between vehicles. Width is based upon what is needed to clear the through traffic with a reasonable amount of safe clearance. Tapers are required for lateral movement of vehicles from the through lane to the turning lane.

This is another specialized geometric feature and as such those vehicle characteristics which influence the design are considered.

Current design practice requires no modification.

Weaving Sections

Weaving sections are areas in which vehicular crossing movements take place through a merge and diverge maneuver. This is accomplished (hopefully) without undue interaction between vehicles. The method of design is from data collected from existing weaving sections; that is, recording the number of vehicles and speed of traffic for the configurations of existing facilities. Accident frequency also is a criterion for weaving-section length.

The observations of existing facilities show the preferences of the drivers in the use of weaving sections. Vehicle performance characteristics probably exceed driver desires and are therefore not critical.

The manner of vehicle operation on weaving sections is more related to driver desire than vehicle performance. Present practice is satisfactory.

Parking Facilities

An explanation or description of parking facilities is not required.

Parking facilities are designed in accordance with vehicle physical size and maneuvering requirements. Additional space beyond that required for the vehicle is left between vehicles for passenger loading and unloading. The facilities are designed to meet the special requirements of size and maneuverability of the vehicles which will use the facility. Thus, these vehicle characteristics are considered in the design.

Present design practice is entirely appropriate. Standards must continue to reflect the physical size and turning radii of vehicles.

Traffic Guidance and Protective Devices

Channelization

Traffic islands are often used in at-grade intersections to direct traffic into definite channels or paths as desired in the operation of the intersection. The purposes of channelization are many and include: reduction of driver decisions, prevention of undesired maneuvers, control of desired movements, refuge for pedestrians, location of signs and signals. To be effective, traffic islands have to discourage or prevent vehicle encroachment, and thus curbed islands are preferred to painted islands. Traffic movements through a channelized intersection should be easy, natural, and cause no confusion to the user.

The layout of channels and the design of traffic islands depend more on driver characteristics than on vehicle characteristics. Vehicle characteristics—often as monitored by the driver—are considered in terms of turn radii, curb height, and driver visibility from the vehicle.

There is no need for additional consideration of vehicle characteristics in the design of channelization beyond those vehicle characteristics which are part of the design of lane width, curve radii, curb height, and visibility.

Guide Posts

Guide posts may serve two purposes. The first purpose, common for all guide posts, is to outline the path which the vehicles are supposed to follow. The second purpose, used in a limited number of cases, is to prevent a vehicle from leaving the roadway, thus necessitating a design of sufficient strength to physically resist vehicle penetration.

For delineation purposes, the only vehicle characteristic considered is the driver's visibility from the vehicle.

In order to prevent a vehicle from leaving the roadway, guide posts have to be constructed with sufficient rigidity and strength to prevent penetration by the striking vehicle. Naturally such prevention will result in damage to the vehicle and therefore vehicle crashworthiness becomes an important factor in the design and placement of barrier guide posts. The primary question appears to be: when does the guide post inflict greater damage than that caused by the vehicle leaving the roadway?

For delineation purposes, the visibility of guide posts is the most important factor, with the post requiring only sufficient strength to support the reflectors or targets.

The use of guide posts as barriers is a mistake from safety considerations as those posts produce a snagging effect which will normally severely damage a striking vehicle. The use of guardrails is urged whenever containment is desired.

Guardrails

The function of guardrails is to prevent vehicles from leaving the roadway at those areas where the departure would result in considerable hazard to the vehicles and occupants.

The accepted standards of design and location are based on the practices employed by the state highway departments throughout the United States. The major emphasis of the standards and recommendations concerns the placement of the guardrails. The need for guardrails generally is determined by consideration of such factors as height of fill, fill slope, road curvature, road grade, shoulder width, climate, roadside conditions, traffic volumes, and accident record. These are usually the result of attempts to measure subjectively: (1) the probability of a vehicle going off the roadway; (2) the likelihood of the vehicle getting into trouble (or recovering after running off the roadway); and (3) the severity of the results of running off the roadway.

There is need for extensive research on the design and placement of guardrails. Considerable work on the design and energy absorption of guardrails is presently being undertaken and is in various degrees of completion. When, and if, vehicle crashworthiness can be related to roadside features, the warrants for installation of guardrails should be reviewed.

Improvements in guardrail design are available which would allow for less severe damage to vehicles retained on the roadway. These improvements should be used whenever and wherever feasible. One difficulty with the problem of guardrail design and selection is lack of uniformity of standards among the states.

Running Speed

Running speed is defined as the speed of a vehicle over a specified section of highway, being the distance divided by running time (the time the vehicle is in motion). In using running speed as a factor in geometric design, the term "average spot speed" (arithmetic mean of the speeds of all vehicles at a specific spot) generally would be a more accurate name for the quantity under consideration. For example, in the design of a deceleration lane, the speed at the entrance to the lane is called running speed, but is actually the average speed of vehicles on the through roadway.

The use of running speed in the design of a geometric feature is a contradiction to the definition of design speed. If a highway is designed for a given speed, all features directly attached to the roadway, such as tapers and entrances to deceleration lanes, should be designed to accommodate vehicles traveling at that selected design speed. It could be theorized that, if average spot speeds are significantly lower than design speed, either the design standards are in error or the design speed is higher than that required or expected of the user.

The present practice of reducing quality of design by limiting special facilities to accommodate only those vehicles traveling at the lower running speed should be eliminated.

TRAFFIC OPERATION PROCEDURES

Traffic operations deal with the actual movement of vehicles on the street or highway and include communicating with the driver by means of signs, signals, markings, and other devices placed on or adjacent to the street or highway. The direct objectives of these communications are to:

1. Inform the motorist of traffic regulations in force at that particular location. Such regulations may be speed limits, stop or yield conditions, no parking, etc.
2. Warn the motorist of those conditions which are potentially hazardous to traffic operations. Such conditions would include sharp curves, steep grades, narrow bridges, etc.
3. Provide the motorist with information for the proper location of his vehicle upon the immediate roadway. Such information is conveyed by lane lines, delineators, center lines, etc.
4. Provide the motorist with the guidance and information necessary for him to reach his destination. Such data would contain information on items such as route number, city name, distances, etc.

Proper communication with the driver results in the desired traffic patterns, minimizes indecisive driver action, and thereby increases the efficiency, safety, and speed of traffic movement upon the facility—in other words, provides a higher level of service.

The following discussion concerns the design, installation and use of traffic signs, signals, and markings, without reference to the warrants for need of the device.

Operational Tools

Communication with the driver is achieved by sight, sound, or feel. The vast majority of methods used rely solely upon the driver's vision to detect and convey the message from the roadway to the driver. Sound is occasionally used to transmit a complete message—airborne radio describing roadway conditions being the most prevalent. The major uses of audio-communications have been to attract driver attention so that a visual message may be transmitted (gongs clanging at railroad crossings, sirens for emergency use of the roadway, etc.). Devices that stimulate the sense of feeling are normally directed at alerting the driver to the fact that a hazardous condition exists or that he is driving on an incorrect segment of highway. Examples of these devices are rumble strips (roughened areas of pavement) and corrugated pavements (occasionally used in paved medians). In either case, a resulting vibration stimulates the sense of feel, and generally an audible whine is also produced which stimulates the sense of hearing.

Visual Communication

The devices acting upon the sense of sight include signs, signals, markings, delineators, etc. In the design and installation of these devices, major consideration is given to the physical and mental characteristics of the driver in respect to his ability to detect and interpret the intended message; that is, the device must attract the driver's attention, convey a message quickly, and be explicit in the information conveyed. Therefore, the size, color, shape, wording, and location of the devices reflect the drivers' ability to see and comprehend. In the case of active control devices (traffic signals) where the signal changes from time to time, driver perception and reaction time has to be considered.

Certain vehicle characteristics have to be considered in the placement and use of visual communication schemes:

1. Vehicle width and height limit the closeness of the device to the vehicle's pathway; that is, signs and other devices at the side of the road have to be far enough back to clear the vehicle horizontally and overhead devices have to be sufficiently high to clear the vehicles vertically.
2. The view from the driver's seat is restricted within certain limits by the vehicle's hood, roof, and some interference from corner posts. All devices intended for visual observation by the driver must be located in such a way as to minimize the effects of these restrictions.
3. At night, vehicle headlights are a major source of illumination for the roadway and the operational devices. When visual communication devices rely upon headlight

illumination, they must be located so that the light rays from the headlights strike them.

4. Vehicle deceleration characteristics are utilized in the establishment of the warning or notification of impending change in active signals—for example, the amber portion of traffic signals. The warning phase should be of sufficient time length for the driver to perceive, decide about, and react to the impending change, and have sufficient time to either stop his vehicle at the proper location or clear the controlled area.

5. Acceleration characteristics receive consideration in the selection of the length of time for the green phase in active signals. The quickness with which vehicles can respond to a go signal may determine capacity and, in special instances, minimum green time.

Audible Communication

Most devices which employ audible signals use noise to alert the drivers to a specific visual message or occurrence. Once alerted, the driver presumably becomes cognizant of an impending change in conditions and adjusts accordingly. Many at-grade railroad crossings use noise to augment the visible signal; emergency vehicles use noise to increase awareness of their approach; a vehicle's horn serves as a warning against encroachment. There have been some attempts to communicate directly to vehicle operators by audible means. Police have used voice and loudspeaker arrangements to control and direct traffic; a few governmental units employ radio to broadcast traffic conditions on the highway to the users.

Communication by audible signal considers the ability of the driver to hear and understand the message being transmitted.

No definite vehicle characteristic is considered per se, with the exception that the presence and use of a radio is assumed in the radio transmission procedures.

Feel Communications

Changes in the roadway surface may be used to alert drivers to changing conditions or improper movements. Rumble strips (transverse strips of coarse roadway materials) have been used to inform drivers of impending dangerous intersections, and corrugated paved medians cause vibrations and audible whines when driven upon. In each case the intention is to notify the driver of specific facts more forcibly.

The success of the devices requires that the driver is startled by a change in the smoothness and quietness of his vehicle.

Vehicle characteristics are concerned with the effect produced when the wheels roll over different types of pavement surface.

VEHICLE CHARACTERISTICS

This section deals with those physical and operational characteristics of on-highway vehicles that have an interaction with highway design or traffic control and operation. Present and future (conceived) characteristics that should be quantified are indicated, and methods for treating the effect of the driver in the man-machine complex are presented.

The durability and total cost of the highway plant should make it a stable element, second only to the constancy of human behavior, whereas there are many variations in vehicles and vehicle types.

It had been expected that the list of pertinent vehicle characteristics could be founded on the format of some appropriate vehicle specification. It appears that no such specification is available. One format was developed by the Automobile Manufacturers' Association, but is much more detailed than is needed for this project. A second one, however, treats parking space requirements, and has been consulted for appropriate characteristics.

If the Automobile Manufacturers' Association's 24-page specification format had been used, many additional items would have appeared in the list of pertinent characteristics. However, the naming of many of these vehicle parts would be superfluous; they could be used to determine maximum (or minimum) values of pertinent characteristics where these values would not be appropriate for highway design or traffic operations procedures. A major portion of vehicle functional characteristic capabilities is modified by the abilities and desires of the driver or passengers.

For instance, many of the components of the running gear and suspension system, tires, wheels, axles, bearings, kingpins, springs, and small hardware could be analyzed to show that the vehicle could proceed along a rough road at speeds that would cause loads just short of damaging the structure. It is obvious that drivers and passengers would not tolerate the discomfort, if not downright physical injury, that would attend such a journey. Thus, any of the parts of a vehicle that contributed to ride quality, and that part of the highway design that affected ride quality, would become a function of human factors, rather than specific design of the parts of the vehicle.

Over-All Dimensions

Length

Over-all length of passenger cars, in conjunction with overhang and turning radius, will affect parking-stall lengths on streets and highways and aisle widths in parking lots. The number of vehicles in queue at traffic control points is dependent on vehicle length, for a given storage length of lane, and also by downvision over the nose. In conjunction with turning radius, vehicle length affects widths of dead-end streets, and in conjunction with track and overhang, affects driveway curb radii and corner radii at intersections.

The behavior of traffic in these situations is dependent on vehicle length in a not-too-direct manner. It is doubtful that density in queue is a linear function of vehicle length. Certainly, corner radii cannot be determined uniquely from a knowledge of this length. Both of these characteristics, the first operational and the second geometric, must be determined from observations of the behavior of real traffic. Of course, with the rapidly growing field of the behavioral sciences it may be possible in the future to make these studies and observations either in the laboratory, by simulation, or on the computer, by mathematical modeling. The main point is that the variability of the driver input may have as much numerical significance as the change in vehicle length, for a given class of vehicles.

The effect of the driver-vehicle dimension combination on highway capacity has been studied both in the United States and abroad (*11, 12, 13*). Conclusions by the U.S. study groups were that up to 15.5 percent of small and compact cars in a traffic stream made no statistically observable difference to the speed and headways of the stream of regular passenger cars.

In the British study, the basic traffic stream was composed of small passenger vehicles. It was found that in such a stream, each vehicle occupied 65 percent of the space (passenger car unit) normally occupied by a larger passenger car. However, when this stream was diluted by 30 percent of larger vehicles, the p.c.u. equivalent of the mini-car rose to 90 percent of a p.c.u.

The small-car driver may take advantage of the size of his vehicle in a homogeneous population of vehicles. However, he quickly adopts an attitude of defensive driving when a minor, but significant, proportion of the stream consists of larger, heavier vehicles. At any rate, the British conclude that small cars can lead to higher vehicle (therefore, people) capacities for the highway.

Space density (lane density), now and in the near future, will be determined best by vertical photography of the highway, for both queueing and speed-headway information. The method can be tedious but, depending on the quality of the photography, can give high accuracies. Lane density can be determined with negligible error, vehicle placement within 8 in., in photographs taken at 400 ft per negative inch. The tracking of turning vehicles is discussed later in this section.

Width

This dimension affects parking-stall length and width on streets and highways and, to a lesser degree, aisle widths in parking lots. In conjunction with vehicle tracking characteristics and downvision over the nose, it affects lane widths to achieve a given lane volume on both straight and turning roadways. In conjunction with turning radius and wheelbase, it affects the clearance required of curbside objects at corners.

A more thorough treatment of the interplay between vehicle width and lane width, and lane width and highway capacity, appears later in this report.

Height

Overhead structures of any sort will be affected by vehicle height. This includes bridges, detectors, wires, traffic signals, signs, lighting fixtures, and tunnel openings.

Maximum Allowable Gross Weight

This figure is pertinent to the determination of maximum allowable axle weight, as limited by highway construction. Also, if non-mountable barriers are to be designed to withstand impact at a given limit speed and angle, maximum lateral load imposed by an axle will be required which, in turn, will be some function of the loading distribution at maximum gross weight.

Therefore, the weight of each unit of single and articulated vehicles is required. Also required is the longitudinal center of gravity location of each unit, specified as the fraction of wheelbase. Several methods for obtaining position of the center of gravity of a vehicle are shown in the SAE *Handbook* (Test Code SAE J874).

Turning Radius

Minimum obtainable turning radius will be achieved at a very low speed condition, with low attendant tire deflection. Turning radius will relate to width for dead-end streets. Corner radii at most driveway openings will be affected only by passenger-car turning radius. Other corner radii will be a function of turning radii of tractor-trailer combinations if access to and egress from the driveways is not to force these vehicles out of the curb lane. The actual profile of an entrance-exit or curbline at an intersection must take into account the transition from linear to curvilinear motion. The transition will include approach speed, steering ratio, design lateral load factor, and observed rate of steering input.

Turning radius, in feet, can be measured from full-scale tests, using chalk or other marker to leave a trace of the axle center lines on the test pad. Outside and inside radius then can be determined by adding and subtracting half of the appropriate tread dimensions, from axle center line to outside of tire wall.

Scale models can be used to determine turning radius, neglecting the effect of tire deflection because of lateral load (*14*). Analytical expressions are offered (*14, 15, 16*) for turning radii and off-tracking of various vehicles and vehicle combinations.

Transition from straight line to minimum radius will be affected by either of two limiting criteria. The first will be one in which the steering wheel-to-front wheel angular displacement ratio is so high that the average driver's input rate will not produce a lateral load factor in excess of the comfort limit. The second will be the antithesis, a steering ratio low enough so that the driver may exceed the lateral comfort limit. A secondary criterion may be average human tolerance to rate of change of radial acceleration (jerk). In simpler terms, the man in the man-machine complex will accept only so much rate of change of curvature. For steering systems that have ratios high enough so that average driver steering input rate will not produce the critical rate of change of curvature, the transition curve should be determined by test. An alternative is to have driver subjects make turns on a simulator. The steering input rate, when applied to the chassis geometry, will yield the transition curve.

Field of Vision

In a paper on "Vertical Curve Design" (*Highway Research Board Bulletin 195*), Loutzenheiser and Haile comment somewhat tartly on the trend of the then (1957) new passenger vehicles toward the long, low look. Their point is well taken; the reduced seat height affects more than sight distance on vertical curves.

Field of view, particularly downvision over the nose, must relate to lane-width requirements. If drivers are to maintain a speed-headway relationship that results in constant level of service from each lane, they must feel assured of their position in the lane and room for maneuvering with respect to the lane edge or other vehicles. How does field of vision affect this assurance?

For certain, the position of the vehicle, with respect to the right-hand edge of the pavement or lane, must be based on a mental extrapolation of the edge from the point where it disappears into the hood profile to where the driver thinks the wheels are. Because any such judgment must include an angular error, the greater the distance to the point of disappearance, the greater will be the error in the estimate of position. The driver will not accept a "negative" error, so the practical result is that a wider berth is given, both to stay on the pavement and to clear parked vehicles. Clearance in a passing maneuver will be some function of lateral angle of vision, and therefore will affect the lane-width requirement (see Fig. 2).

It is not expected that numerical values for clearance margins can be determined from just a polar plot of field of view. These values must be derived by testing, on a statistical basis, with many driver subjects. A single test vehicle probably should be used to eliminate variables other than the field of view. The latter could be varied by modeling of the hood and fenders or masking on the windshield. This is the kind of testing that could be done easily.

Returning to the comment on seat height, the different perspective of the road edge afforded to the driver by reason of difference in seat height also may affect the lateral position estimate. Additionally, both the handling characteristics of the vehicle in tracking and vehicle width will be variables that should associate with lane-width requirements.

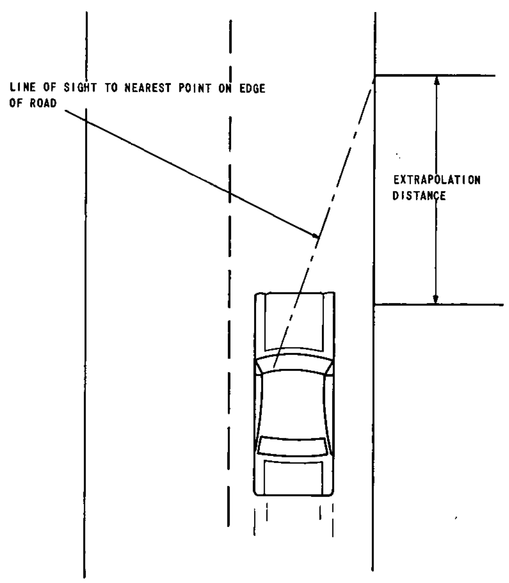


Figure 2. Shortest line of vision to righthand edge of road.

Vertical field of vision upward should have an effect on where a driver will stop a vehicle when approaching a traffic signal. (It is safe to assume that he or she will not want to crouch down to keep the signal in view.) Thus, the effective stop line will depend on upward vision. Stop-line location, in turn, will affect the time required for a given vehicle in queue to clear the intersection after the signal has changed to green.

Measurement of the field of vision should be made in semi-vertex angle about an axis longitudinally directed through the driver's eye level. It would be plotted on a polar coordinate layout, using vertically upward as the zero reference and azimuth taken clockwise from the driver's position and view. It is apparent that some discrete value may be used for the height of the driver's eye, when highway designers determine geometrics for which field of vision and sight distance are criteria. This value may be determined statistically as the average of a large sample of drivers seated in a representative selection of private and commercial vehicles. It is also possible that an envelope of eye positions may be used that would be determined in a similar manner. The envelope might contain some percentage of the total sample. Both Lee (*17*) and Stonex (*18*) show values for height of the drivers' eyes. Lee's data (*17*) are from observations of real traffic, and therefore would tend to be valid statistically. Lee shows a steady reduction in height of eye of the average driver-vehicle combination, from 4.8 ft in 1931 to just under 4.0 ft in 1959. Because of the significant portion of the population of passenger cars giving driver's eye heights of 3.75 ft to 4.0 ft, as reported in the AASHO *Policy*, it would appear that the 3.75-ft value established in the *Policy* is valid for design.

It is evident that desired compatibility probably will not be guaranteed for every case. It would be well for highway and vehicle designers to consider some scheme for making the driving public aware of when the driver's eye height is outside of design standard limits.

Acceleration Capability vs Speed

Acceleration capability of vehicles, in general, can be divided into two categories, for the purposes of this study. There is some level of acceleration, or narrow band of acceleration, above which drivers or passengers will find discomfort. Those vehicles that have acceleration capability above this level, or the center of the band, fall into one category. Those vehicles with lower capability fall into the other.

It may be assumed that the high acceleration available in vehicles of the first category will be of little or no importance in either their performance on the highway or in traffic operations. Any design criteria to be based on maximum acceleration should use the driver/passenger limit level, a value that must be determined statistically from a large population.

On the other hand, low levels of acceleration (climb) will be a consideration in highway design and traffic operations. Illustrative examples will show the interaction.

Until relatively recently there have been no penalties imposed on slow drivers. The 30-mph driver in the two-lane 50-mph highway was considered to be exercising his individual freedom and being conservatively safe. (There is ample opinion to the contrary about the safety of this type of driver.) The fact that he was imposing his will on the rights of others, who would otherwise elect to drive at the speed limit, once past the bottleneck, was not an important consideration to legislators of traffic ordinances. Today there is a slow movement in the direction of establishing minimum speed limits on some of our higher-type highways. What does this mean in terms of the vehicle?

It means that there are already many roads in the United States where most commercial vehicles, and some passenger vehicles, cannot maintain the posted speed limit. Where these roads do not have two lanes upgrade, traffic movement is penalized by the presence of these vehicles. When traffic is heavy, even dual-lane operation is reduced below the capacities that could be attained by vehicles with adequate climb capability.

If high minimum speed limits are to be imposed, then specifications for vehicles will have to guarantee a sufficiently high power-to-weight ratio so that adequate rate of climb will be available. Much more specifically, a minimum torque at the driving wheels shall be specified as a function of vehicle speed, weight, and tire diameter. (This is equivalent to specifying draw-bar pull for a locomotive.)

The required value for torque may be derived from the grade to be climbed, speed to be maintained, altitude, and an arbitrarily chosen headwind. Vehicles may be tested on a dynamometer, loaded to simulate the upgrade. Tire and transmission losses will be included by such testing but aerodynamic drag will have to be computed and added to the dynamometer load. It is pointless to discuss advertised power, because such performance figures often are obtained without cooling system pumping losses, fans, or generator. Further, the use of automatic transmissions, particularly the turbine type, makes it difficult, if not impossible, to predict engine speed (and full throttle torque) for a given speed and drag.

If bona fide curves of engine performance and "carpet" curves of transmission characteristics can be obtained, reasonably acceptable accuracy can be maintained in computing acceleration and climb capabilities of vehicles. Engine data would be typical power vs rpm at full throttle, corrected to standard atmosphere. Transmission data would be curves of power loss and slippage vs output shaft torque and rpm. Driveshaft and differential gearing losses may be computed from long-established data on gearing. Tire deflection and hysteresis losses would have to be acquired as a function of rolling speed, inflation pressure, and wheel loading. Temperature and road-surface effects may be secondary. A procedure for actual testing of reserve tractive ability (for climb and acceleration) is shown in the SAE *Handbook* (Test Code SAE J872). Whether the test code was used is not stipulated but Wright and Tignor (*19*) report weight-power ratios for a sample size of 1,026 vehicles. These 1963 data are the most recent published.

The antithetic point of view to specifying a minimum allowable speed is loss of service of the highway, for those places where speed limits cannot be maintained by the lower power-to-weight ratio vehicles. It has been the practice of the highway designer either to accept the loss or to provide climbing lanes at locations where grade and altitude made serious reductions in the speed attainable by these vehicles. The new *Highway Capacity Manual* (*1965*) gives some clue to the effect of low power-to-weight ratios in its Figure 5.1. If enough basic information is made available on specific vehicles, the types of curves of Figure 5.1 can be synthesized. Otherwise, any needed data will have to be supplied by road tests.

In "Driver Passing Practices" (*Highway Research Board Bulletin 195*), O. K. Normann concluded that changes in current (1957) vehicle design and driver performance did not warrant changing the current marking of no-passing zones. His reference base was the performance of 1938 vehicles and drivers. He did note that some highway design practice could be improved by taking into account the later technical information. The same thing can be said at this time.

If it is found that the acceleration and passing practices of drivers have changed significantly from 1957 to the present day, new sight-distance standards might be set for passing maneuvers. Again, it must be noted that the vehicle characteristic alone does not furnish sufficient evidence to warrant the changes. It is necessary that the driver-vehicle combination be observed and evaluated on a statistical basis. Time and distance in the passing lane should be plotted against speed of the vehicle being passed. If a significant change is found between Normann's 1957 data and that of the present day, the no-passing-zone markings can be changed to suit. If the markings are suited to the highest accelerations available, the point should be publicized so that drivers of lower power-to-weight ratio vehicles may not overextend themselves.

A final application of vehicle-acceleration capability to the highway is the length of acceleration lane required to permit satisfactory merging on entrance ramps to limited-access highways. By satisfactory merging is meant that the speed differential between merging and mainline vehicles shall be small enough not to cause shock waves to propagate upstream in the lane adjacent to the acceleration lane.

The effect of vehicle-acceleration capability might be seen in several areas of traffic operation. Quite obviously, if the achievable acceleration is below the previously discussed human tolerance limit, it will affect the rate of departure of vehicles stopped in queue at a traffic signal. Whether drivers and passengers will adapt to the increased acceleration capability of passenger cars with high power-to-weight ratios remains to be seen. It would require an appreciable program of before and after data collection to prove that the power effect was indeed statistically significant.

Similarly, it is possible to use high acceleration capability (and deceleration) in weaving maneuvers, to shorten the lane-changing time and distance. It will require observation of a large population of events to prove the significance of any change in this characteristic.

The effects of road-surface condition and tire design on peak acceleration are discussed elsewhere.

Deceleration Capability vs Speed

It is likely that maximum braking deceleration for all highway vehicles exceeds the comfort limit for passengers and drivers. There may be some exceptions in the case of tractor-trailer-trailer combinations, but these would be rare. Therefore, braking capability, as in the case of acceleration, can be classified into two categories: above and below the comfort threshold. The maximum values obtainable might be used in situations that may be described as urgent or emergency. The lesser decelerations will not be a function of vehicle capability and, probably, would be used for normal operations.

Maximum deceleration, in ft per sec per sec, if needed, should be determined by two methods. The first would be with wheels locked, the typical "panic stop." It would be done on dry pavement, of various types if necessary, through the speed range of interest. Second, this same schedule should be followed with the tires just short of skidding (zero slip). Although it is unlikely that the average driver will be able to obtain such a braking condition, there are developments of non-skid braking systems that will minimize loss of control in emergency stops.

It would appear that sustained braking capability of a vehicle would be a critical factor in determining the length or steepness of downgrade on which safe operation could be maintained. The present practice of using lower gears to provide engine braking may be adequate where solid drive transmissions are used. In some automatic transmission installations, the engine may not be used effectively in this manner. Reliance for speed control and stopping on downgrades must be on the wheel brakes.

Thus, the principal interaction between braking capability and the highway is in a vehicle's negotiating a downgrade, under adequate control.

Sustained braking tests might best be performed on a dynamometer, because the drag load can be precomputed as a function of grade and vehicle air and engine drag characteristics. This would eliminate any dangerous situations that might be presented if the brakes were to fade in a real road test.

Stopping sight distances, whether due to intersections or traffic control signs or signals, and lengths of deceleration lanes, usually are determined from statistically derived deceleration levels. The observations of real traffic should be made for level and grade conditions for a wide range of approach speeds; for example, 20 mph to 80 mph.

Certain traffic flow characteristics derive from the maneuverability of the vehicle, in which braking is a factor. In particular, the average speed-headway relationship exhibited by a driver population on a given segment of highway will be affected by braking capability. Because the speed-headway relationship is the direct contributor to highway capacity, it is plain to see how braking capability can affect the amount of transportation a highway will support.

In the discussion on deceleration levels, from the viewpoint of driver preference, the AASHO *Policy* of 1965 states that comfortable over-all deceleration to a stop, from 70 mph, was about 9 ft per sec per sec. Further, it is stated that the deceleration decreased as initial speed decreased. These 1940 data (*20*) are not noticeably different from quite recent (1965) observations of rural traffic approaching an intersection controlled by a flashing red signal. The latter data (*21*) do not cover the total range of initial speeds of the earlier investigation, but both the trend and the values in the portions that overlap are close enough so that they are in agreement.

Of course, no significant changes in passenger-vehicle brake design have occurred in the 25-year period separating the documentation of the results. Results of braking tests on all types of vehicles, over the years 1942 to 1963, showed that some improvement in emergency-stop performance has been obtained (*22*). For instance, a linear regression on passenger cars showed that the center of the 95 percent confidence level band on stopping distance from 20 mph was just over 23 ft for 1938 models. The stopping distance for 1963 models was 19.5 ft, brake system application plus braking. Similar performance improvement was found for all types of commercial vehicles.

However, it is emphasized that the improved performance was for dry-pavement emergency stops, not the more typical performance desired by drivers. It would appear that current practice based on the AASHO figures should be valid.

Steering-Wheel Angle vs Front-Wheel Angle

The mechanical ratio between the steering wheel and the front wheels will have a direct bearing on the track of most vehicles in executing a turn. Also, it will be a major factor in steering response or handling quality at high speeds, in conjunction with other dynamic characteristics of the vehicle's running gear and suspension system.

Measurement of front-wheel angular motion should be made for each wheel, designated as inner and outer, the inner wheel being the one toward the center of the turn. The reference line should be the longitudinal center line of the vehicle and the angular motion should be measured as the component in the plane of the ground (surface).

In theory, these measurements can be used to compute turning radius for fully articulated vehicles, if it is assumed that the sideslip is the same for all tires. If this assumption fails, it will be necessary to determine turning radius vs steering-wheel angle by test. It is likely that in turns made at speeds that produce significant side forces, some deviation from the theoretical values will occur, thus requiring testing. It may be that a systematic test program might produce acceptable correction factors to be applied to the theoretical results, so that testing will not be necessary universally. Parameters of interest in applying correction factors may include linear speed, height of center of gravity, tire size, and tire pressure.

Rate of angular input at the steering wheel has been discussed under "Turning Radius." Transition from linear to curvilinear motion may depend on rate of angular input at the steering wheel and the mechanical ratio to the front wheels, at a given steering-wheel displacement angle.

Tire Coefficient of Friction on Various Surfaces

For most vehicles, tire coefficient of friction in the direction of rolling will limit the braking decelerations that may be realized. For many U.S.-built passenger vehicles, the same coefficient of friction will limit the accelerations that may be produced. This applies to the case where maximum coefficients are obtained—dry, grit-free pavement conditions.

The combinations of types of paving, tire condition, wheel load, tire pressure, amount of moisture and its state, and amount of loose material can produce almost a continuum of coefficients of friction, down to the lowest values normally obtained. The latter probably result from smooth tires sliding on wet ice. Superelevation usually is limited by tire coefficient of friction on an icy surface.

For the computation of stopping sight distance, the AASHO *Policy* for 1965 gives values for coefficients of friction vs speed for wet pavements, to be used in the braking distance equation. The values vary from 0.36 at 30 mph to 0.29 at 70 mph. The program reported by Close and Fabian (*23*) consisted of 334 tests on 53 wet road surfaces of various levels of wear. The data summary plots show differences in coefficients of friction for the several concrete aggregates from 0.27 to 0.54, and variations from 0.20 to 0.54 for bituminous pavements.

Further variations of coefficient of friction for tires on wet pavements are shown by Trant (*24*, Figs. 9, 11, 13). The variations are due to depth of water on the surface (0.05 in. to 0.3 in.), tire inflation pressure (18 to 40 psi), and type of tread.

The conclusion is drawn that the curve of coefficients of friction vs speed, as shown in Figure III-1B of the AASHO *Policy*, is conservative at the low-speed end, for average pavements, but may be realistic for worn or low-quality surfaces and for worn tires. No change in the currently used values is warranted.

Methods for testing tires for friction coefficients are described thoroughly in both references cited.

Wheel-Suspension Characteristics

Maximum braking forces are limited by the coefficient of friction on the road and wheel loading. Maximum acceleration forces also may be subject to these same limitations, especially for cases of reduced friction coefficients.

If a vehicle were a rigid body, wheel loading during acceleration and deceleration would be easy to compute, knowing the position of the center of gravity (C.G.) and the wheelbase. However, springing of the vehicle and the resulting variation of the position of the C.G. will vary the reactions at the wheels, during acceleration and deceleration.

Therefore, if the effect of wheel loading on traction force is to be computed, the deflection characteristics of the wheel suspension system must be known. They can be expressed as vertical motion of the sprung portion of the vehicle, at the wheel center lines, with variations in gross weight of the vehicle. Longitudinal location of the C.G. can be determined from the wheel reactions. Height of the C.G. then can be found by measuring the wheel reactions with either the front or rear wheels elevated to incline the vehicle at about 15° to 20°. This procedure is precisely equivalent to determining C.G. by the method of suspending a body successively from two different points and noting where the suspension lines cross (pendulum method). The procedure may not be useful for those vehicles in which the springing is so soft that a significant longitudinal deflection will take place when the vehicle is tilted nose-up or nose-down.

In many cases, the vehicle in actual use will carry a load which will be a significant portion of the total weight. Almost never will the C.G. of the load coincide with the C.G. of the empty vehicle. The manner in which the combined C.G. can be computed is treated under "Ratio of Height of Center of Gravity to Tread Width."

Natural Frequency—Front and Rear Suspensions

The highway design and traffic control manuals do not treat the subject of irregularities in the road surface, but there is ample testimony that rough roads do exist. Washboard gravel roads are well known, and this effect even occurs in paved highways, specifically in bituminous surfaces on the approach to intersections, traffic control signals, and other areas where significant braking occurs.

At any rate, these excitation sources do exist in the roadways. They can lead to producing impulse frequencies that are in resonance with wheel suspensions of some vehicles. When this occurs, the vehicle practically can take off, resulting in poor stability and control, possibly loss of control. The remedy for this situation can be to smooth the highway to a specified wavelength and amplitude, get the wheel suspension natural frequency out of the resonant range, or damp the wheel motion almost completely. The last could make for a very hard ride.

If any course of action is to be taken, either by highway or automotive engineers, the natural frequency of the wheel suspension should be known. Uncoupled frequency for front and rear wheels may be obtained separately by installing an unbalanced wheel and driving it at increasing speed until resonant oscillation of the suspension takes place. The wheel can be driven by a dynamometer (unpowered wheels) or through internal power.

Natural Frequency—Sprung Mass

In the same way that wheel suspensions can be excited into serious oscillations, long waves in the paving of the highway can produce uncomfortable or dangerous vertical or pitching motions in the sprung mass of a vehicle. Excitation of rolling movements is less likely to occur, but is a matter for consideration.

If highway engineers are to specify limiting surface wave forms, or if automotive engineers are to modify suspensions to eliminate most prevalent vertical or pitching motions due to road surface excitation, the sprung mass natural frequencies must be known. Tests for these frequencies may be conducted or, if enough is known of the dynamic characteristics of the individual wheel suspensions, the frequencies may be computed.

If tests are conducted, they would be valid only for the mass and C.G. locations used for the test. The wheels of the vehicle could be supported on small, pneumatically, hydraulically, or mechanically pulsed platforms. Vertical input frequencies could be varied until the vehicle bobbed (from simultaneous jogging of the wheels), pitched (from time-related pulses on the front and rear wheels separately), or rolled (from time-related pulses on right and left sides separately).

In a rigorous analysis of natural frequencies for the sprung mass, some account would have to be made for the damping effects because of aerodynamic forces and also the modifying effects because of gyroscopic precession of the engine rotating parts. However, for practical purposes it is estimated that these effects can be neglected because they are small when compared to the other vehicle characteristics.

Headlight Illumination

Until the day that plane polarization of headlamps and windshields becomes general practice, the intensity and field of illumination by headlights must have a profound effect on highway design and marking. (Solutions other than polarization may be possible; certainly none are considered to be feasible at this time.)

For night operations, vehicle illumination of the highway and its ancillary equipment is restricted because of the constraints imposed by the opposing driver. Therefore, design features are affected, such as vertical curvature, horizontal curves (especially corners), vertical and lateral locations of signs, with respect to the lane, sign size, color, and lettering arrangement, pavement markings, and, to a degree, lane width. It should be expected that performance on narrower roads will fall off during the hours of darkness because of increased clearances required by opposing drivers when operating at given speeds.

Heights of barriers between adjacent opposing lanes should be affected by height of headlight and shape of beam. Widths of medians also will be affected by shape and intensity of beam. In both cases a glare threshold will be a determining factor.

The measurement of headlight illumination is done by photometry. Using the longitudinal axis through the headlamps as the origin of a polar coordinate plot, profiles of equal illumination (foot-candles), taken at some arbitrarily chosen distance, should be drawn. The radial offset may be shown either as a radial distance or as semi-vertex angle. Given that the beam pattern for the standard headlamp is consistent among all manufactured brands, the desired location of the beam pattern can be realized by specifying headlight height and beam angle, or combinations thereof.

Height of Center of Gravity

The design of crash barriers and their supports will have some dependency on the height of the C.G. of loaded vehicles. When loss of control of a vehicle occurs, in the region of such barriers, their intended function is to contain the vehicle or return it toward the road with minimum rebound velocity. The vehicle is not expected to be able either to vault or somersault over the barrier.

If the location of the C.G. is sufficiently above the height of a barrier, it is possible for enough rolling moment to develop, as the result of oblique impact, to roll the vehicle over the barrier. Since the C.G. height cannot be specified at the free will of the vehicle designer, compatibility of crash barrier design with the vehicle will be incumbent on the highway designer.

Height of Door Opening

If a door is to be useful, when a vehicle is parked parallel and adjacent to a curb, the bottom edge of the door should be high enough to allow it to be opened. At one time in the history of the U.S.-built passenger car this compatibility posed no problem, so that whatever arbitrary standards were used to determine curb heights went unquestioned. It is no longer true that practically every door will clear practically every curb. Therefore, it is necessary to mention that there is an interaction between these two dimensions.

The functions that a curb performs appear to be manifold and were not conceived simultaneously. As a delineator between the paths for people afoot and those mounted or in carriages, it would be difficult to show analytically what the height should be. As a drainage barrier, to keep the footpath from being inundated, some grade separation could be computed, considering rainfall, slope of the street, etc. And as a barrier to keep automobiles from invading the sidewalk, some arbitrary height might be assigned so that the motorist would be certain to known that the vehicle tires were in contact with the curb. Once some minimum curb height was established that would satisfy the several requirements, it would seem that the rest of the compatibility problem rested with the vehicle designer.

The pertinent dimension should be measured linearly above the pavement plane, taking into account the slope caused by crown in the street paving, with the door fully open. A further deflection will occur as passengers alight from the right hand side of the vehicle, when their full weight is applied to the threshold of the door opening.

Tire Outside Diameter

There are many policies, codes, handbooks, and manuals on the design of highways and specifications on materials of construction. Noticeable by its absence is any specification on maintenance procedures. So, although a road may have been designed and constructed originally as a serviceable and safe highway, its condition can deteriorate to the point where it becomes uncomfortable to ride on, destructive to the vehicle, or unsafe, in that order. The last can happen when the surface profile is discontinuous to the point that momentary loss of control occurs if a wheel hits a bump or pothole. The effect (severity) that the discontinuity has will be some function of the outside diameter of the tire; the larger the tire, the less the shock, particularly in the case of potholes.

Because there is an interaction between pavement roughness and tire outside diameter, the latter is of interest. It would be measured in inches.

Probably a specification for maintaining highway surface to within some contour limits would consider the vertical and horizontal accelerations that may be imparted to a wheel. Controlling factors will be wheel size and contour of the discontinuity in the surface, plus tire pressure. What the vehicle feels will include the characteristics of the wheel suspension, spring rate, geometry, and shock damping by the snubbers.

Handling Quality

Handling quality is used to represent a loose list of behavioral characteristics of a vehicle, the sum of which, when compounded and integrated, results in some desirable (or undesirable) response to human control. Whatever has been done to quantify handling quality has been carried to its highest state in the evaluation of airplanes and space vehicles.

Handling quality might be defined, for a highway vehicle, as the precision with which a vehicle can be made to follow a path desired by the driver, in view of external disturbance factors and the degree of physical and mental effort exerted to achieve this precision.

Certainly the preciseness of maintaining a desired path will affect the lateral clearance to be provided for a vehicle (lane width). Some of the external factors that will affect the precision adversely are:

1. Steering under various road surface and irregularity conditions, with no sharp discontinuities.
2. Effect of bumps and potholes.
3. Winds and gusts.

Like some other vehicle characteristics, handling quality will be time-related. A driver can exert the concentration and physical force required to maintain a certain preciseness of path at the beginning of a trip. Depending on the vehicle, this capability may deteriorate slowly or rapidly as time progresses.

It would appear to be difficult to identify all of the detailed physical characteristics of the vehicle that should be quantified in order to arrive at a measure of handling quality. It is evident that steering ratio will be a factor. It is equally evident that aerodynamic side force coefficient will be important, especially at high speeds. Certainly, wheel suspension parameters will have significant effects.

The measurement of handling quality may be a difficult procedure, particularly if any degree of repeatability of data is to be expected. Probably it is safe to say that the variability of conditions in a real traffic environment would eliminate the highway as a test site. A test track, on which carefully controlled surface conditions could be maintained, might be more suitable. Here it would be possible to establish a nominal path to be followed and deviation from the path could be recorded (photographically or electrically) as a function of elapsed time and position along the track. Control over aerodynamic inputs on such a test track would present a problem. Because the road surface could be modeled to desired irregularities, there would be no question of repeatability of these inputs.

A driving simulator could be built in which the driver's station could be made to feel all of the inputs from the road, as well as the buffet caused by gusts. However, such a simulator would require a photographic (movies) presentation of movement along the highway, the presentation being moved laterally in response to steering movements. In addition, all of the vehicle suspension and steering characteristics would have to be expressed as transfer functions in the simulator. Although the latter might be useful for the detailed design of vehicles, it would pose an additional burden just to measure the tracking capability of the man-machine combination. It would serve no useful purpose, in the present project, to discuss details such as static and dynamic oversteer and understeer, tire side force characteristics, changes in wheel direction angle because of vehicle roll angle, etc.

It would appear that the best compromise would be the use of a test track facility. Measurement of deviation from the nominal path would be as currently performed on the research agency's test facility (an electrical field generated by a cable on the track and two pick-up coils on the vehicle) and recorded on magnetic tape for ease of analysis. Effect of winds and gusts could be noted by recording these and developing power spectral densities for comparison purposes for the same vehicle and driver.

To conclude, handling quality would be measured by determining average deviation from a nominal path on a specified test track, having driven the vehicle over the track for a specified period of time and at an average speed.

Vehicle Underclearance and End Clearance

There are relatively few places on streets and highways where a change in grade (slope) is so great and so sharply defined that the resulting discontinuity poses a threat to the underside of a vehicle. However, ramps and entrances and exists to driveways frequently have to meet unusual conditions, resulting in local rates of change of slope that may permit either end or the center of a vehicle to contact the pavement.

If compatibility is to be maintained between the vehicle and the highway, some standard will be required to which both can be designed on a not-to-exceed basis. A simple way to guarantee underclearance is to specify a standard radius of curvature to be applied between adjacent wheels on a vehicle and the underside of the vehicle. No crest profile would have a radius of curvature as small as the standard and no vehicle would have one as large. This situation is shown in Figure 3. Thus, compatibility is guaranteed if:

$$R > R_v \quad \text{and} \quad R < R_H$$

It is assumed, for purposes of unambiguity, that R_v is measured or computed with sufficient load in the vehicle so that all springs are just fully compressed (or suspension travel limiters closed) and the tires deflected correspondingly.

In the case of a sag curve, the low points at the ends of the vehicle become critical. Again, a simple way to guarantee end clearance is to specify a standard radius of curvature to be applied to the adjacent wheels and any point to the vehicle ends. No sag curve would have a radius of curvature as small as the standard and no vehicle would

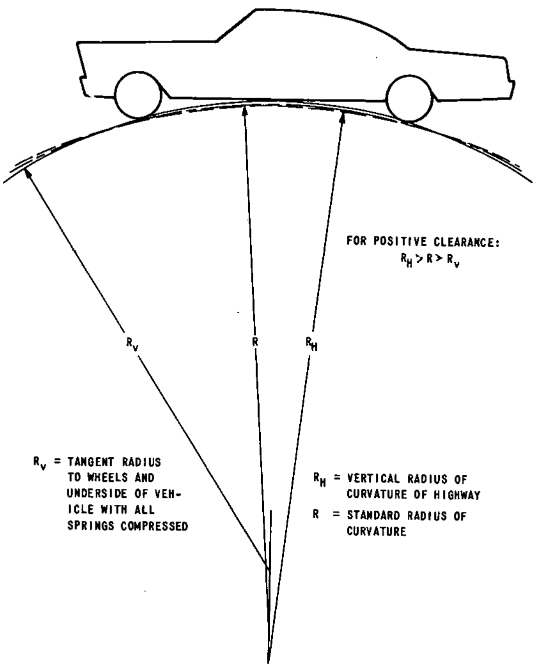


Figure 3. Underclearance on a crest curve.

have one as large. This situation is shown in Figure 4.

Where changes in slope of the road surface, ramp, driveway, or otherwise, are caused essentially by the intersection of two planes, then the angular deflection must be limited in a manner that takes into account several other factors. For instance, underclearance on a crest could be guaranteed if it could be shown that, over the vehicle wheelbase, the intersecting planes would fall within *R*, as shown in Figure 5. End clearance on a sag profile would be guaranteed if some angle, α, was exceeded in the vehicle and not reached on the road surface. This is shown in Figure 6.

The criteria suggested in the foregoing discussion and shown in the several figures are arbitrary. For instance, there are no constraints on the loading of a private passenger car; only the judgment of the driver is the deciding factor. And it is this passenger vehicle that is most apt to be critical in clearing the highway discontinuities. Therefore, the suggestion for using fully compressed springs and corresponding tire deflection is in recognition of the fact that the vehicle should be loaded in a reasonable manner, with a C.G. location such that, under positive vertical load factor, all of the springs bottom simultaneously. There are no guarantees that this will happen. Also, there is some inconsistency in the use of the fully compressed suspension for the crest curve condition shown in Figure 3. Actually, a vehicle traveling over the path, R_H, at some velocity, V, would be lifted from its nominal spring position by reason of the centrifugal acceleration, V^2/R_H.

Ratio of Height of Center of Gravity to Tread Width

Limiting radii of curvature for most curves on rural highways will be dependent on the amount of lateral load factor that is permissible (in excess of that reacted by superelevation). For practically any passenger car, any passenger-limited lateral acceleration will produce roll moments that will be far from critical for the vehicle.

However, commercial transport vehicles, especially when loaded, do not have a very low ratio of C.G. height to

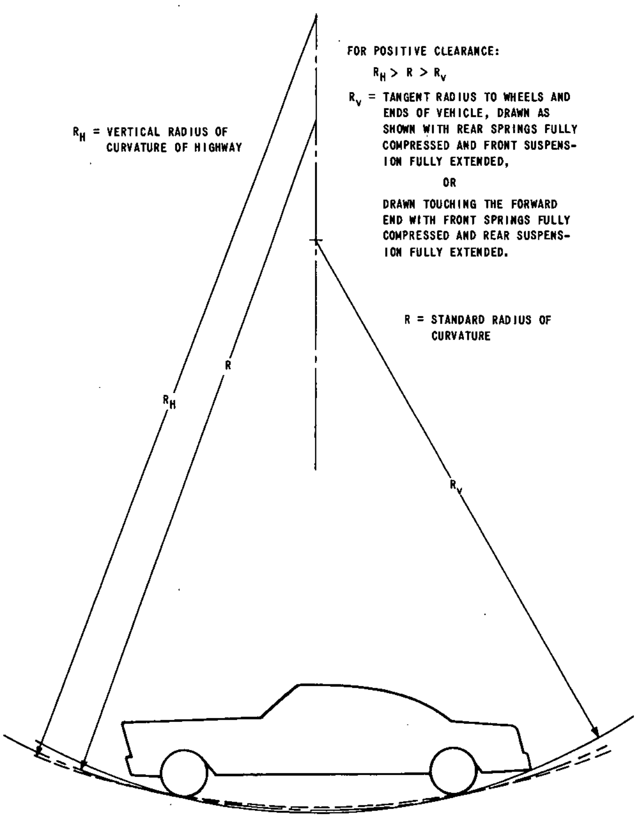


Figure 4. End clearance on a sag curve.

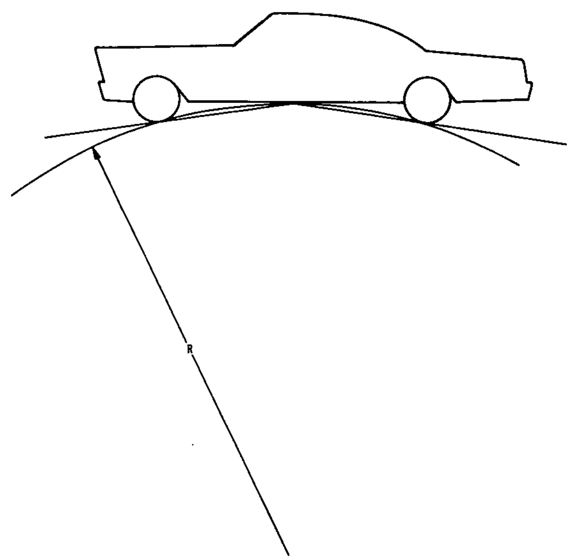


Figure 5. Underclearance on a ramp.

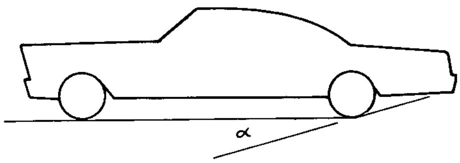
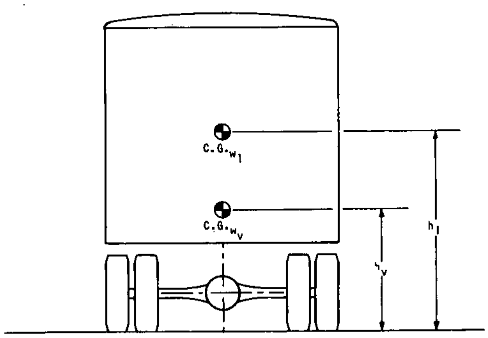


Figure 6. End clearance on a ramp.

tread width. Therefore, it is possible for such a vehicle to be driven around a curve at a lateral acceleration that could produce a near-to-critical (or overturning) roll moment. The combination of operating speed, radius of curvature, and superelevation should be compatible with the C.G./tread-width ratio. Unfortunately, the latter is not solely a vehicle characteristic, but depends on the cargo and the matter of loading. An approach to guaranteeing safe operation under these conditions is to establish a design standard for curves based on some limiting C.G./tread-width ratio (or specify a ratio that will operate safely at a given lateral load factor, the latter to be shown as a speed limit for a given curvature). If the vehicle operator exceeds this ratio because of an unusual loading requirement, the vehicle should be speed-restricted on curves.

Measurement of C.G. height is impractical in normal operations. It would best be done as for cargo and passenger aircraft. Unloaded weight and C.G. height would be known, and a C.G. computed for the weight and position of the load items. The two then can be combined, as shown in Figure 7. It should be noted that the computation involves only a vehicle unit; the trailer of an articulated combination must be dealt with separately. For practical purposes, a tractor-semi-trailer combination can be treated as a unit because roll moments at the front of the trailer are transmitted through the "fifth wheel" coupling. No alleviation of critical roll moment should be credited to the fact that the center lines of the two elements of the combination are not coincident in a turn, because the angle between them would be negligibly small. A single-unit vehicle is assumed.

If the vehicle is a tractor-semi-trailer combination, the individual values of the tractor and empty trailer weights and C.G. heights would be used in the numerator of the equation in Figure 7. If the load is non-homogeneous and made up of many units, a typical balance table would be useful, as shown in Figure 8.



$$h_c = \frac{h_v w_v + h_1 w_1}{w_v + w_1}$$

IN WHICH w_v = WEIGHT OF VEHICLE
w_1 = WEIGHT OF LOAD
h_c = HEIGHT OF C.G. OF VEHICLE-LOAD COMBINATION

Figure 7. Height of combined center of gravity of vehicle and load.

Side Overhang Angle and Height

Recent highway design has included the use of median barriers that are intended to be non-surmountable and essentially non-damaging to vehicles approaching them within a specified angle of obliquity and specified speed. Although some concessions might be made in the design of these barriers to wide, low-profile vehicles, the vehicle designs should be constrained, if metal damage is to be avoided.

Establishment of some limiting angle, β, may be made by the barrier designer such that a vehicle overhang angle of less than β will insure no scraping if the barrier is contacted within the design angle of obliquity. The method for measuring β is shown in Figure 9.

The side of the vehicle next to the barrier should be loaded vertically at the spring center lines until the travel limiters are slightly compressed. A precise loading condition cannot be specified because the lateral acceleration on contact with the barrier will not be known, even for a particular approach angle and speed, because of differences in tire pressure and vehicle suspension. An arbitrarily selected nominal value can be added to β in order to accommodate tire and suspension deflection.

Height of the overhang may be of some importance in parallel parking next to a curb. For compatibility (no damage to the vehicle), there should be vertical clearance between the curb and the overhang, with the vehicle loaded.

CENTER OF GRAVITY COMPUTATION TABLE

ITEM	WEIGHT (w)	ARM (h)	MOMENT (M)
TRUCK OR TRACTOR			
TRAILER			
TOTAL		TOTAL	

AT ANY ITEM, MOMENT (M) = w x h

HEIGHT OF COMPOSITE CENTER OF GRAVITY, $h_c = \frac{\text{TOTAL MOMENT } (\Sigma M)}{\text{TOTAL WEIGHT } (\Sigma w)}$

Figure 8. Typical form for computation of center of gravity.

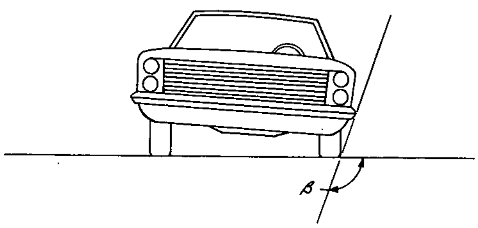


Figure 9. Side clearance angle.

Stoplight Position and Actuation

Highway capacity is largely a function of car-following behavior (speed vs headway). Car-following studies (*25*) have shown that drivers will maintain smaller headways for several reasons, one of which is improved information on the intentions of the lead driver, or better still, the driver in the second vehicle ahead.

The placement of a stop signal on a vehicle has much to do with the distance to the rear that the signal may be visible, which will affect capacity. Also, the sooner the lead driver's intentions can be communicated, the greater will be the margin of time for reaction by the following driver. This, also, should affect capacity. Therefore, the vehicle characteristic that is of significance here is the manner of sensing driver intention. Recent practice has been to sense braking only, from build-up of braking fluid pressure in the hydraulic or pneumatic brake actuation equipment. One current deviation from this almost universal practice is to use brake-pedal movement to actuate the stoplight switch, a scheme that does not appear to fulfill the need for accurate information on driver intention.

New Characteristics in Future Vehicles

Concern with future vehicles and transportation systems comprises a considerable segment of the transportation research interest of the research agency. Naturally, the persistence of the street and highway system, as we know it today, is an accepted fact of life. No radical evolution or revolution that would make this system obsolete is anticipated.

There are, however, ideas for personal, individual transportation systems that can have a profound effect on the numbers and sizes of vehicles that will constitute the traffic demand for these streets and highways. The vehicles can vary widely in performance capability, but, in general, the same parameters that apply in describing the characteristics of current vehicles will be appropriate to the new types. For instance, there is a reasonable probability that a dual-mode vehicle will be developed, dependent on internal battery power for propulsion on the streets but on external (third rail) power for high-speed operation on an automated guideway. Storage battery technology, while experiencing dramatic improvements, still appears to be such that moderate speeds, modest accelerations, and relatively limited cruising ranges may be expected of these vehicles. The relationship of the vehicle to highway design geometry should not be at all different than it is today. Again, the numbers may change, but the descriptive parameters probably will not. (Parking-slot sizes may change, but the method of determination of that size will not. And the same might be said of the volume capacity of streets of given widths.)

There may be an attempt to raise cruising speeds on limited-access highways by the use of vehicles that are much more functionally designed for high speed than are today's offerings. Still, there does not appear to be anything exotic about the new vehicle that will affect the basic concepts of highway design. There may be more of or less of one thing or another, but they will be the same kinds of things. (One scheme, using human guidance, suggests the use of 15-ft lanes; another, employing a form of rail guidance, needs only a foot more lane width than the tread of the vehicle.) Acceleration capabilities should remain essentially unchanged, when compared to today's higher power-to-weight ratio vehicles. Braking from high speeds may be more reliable, but the limiting decelerations are not expected to change. And so on, for the rest of the vehicle. For instance, the use of periscopic, forward-vision displays may make a significant improvement in sight distance from these vehicles, including better headlamp placement, but it would have no effect on the minumum sight distance requirement, as determined from the presently used equation. These sight distances will have to be designed into the highway to satisfy the needs of the more critically located (lower) eye height of a large segment of the driver population.

Essentially the same conclusions may be drawn for transport vehicles of the future. Sizes may change, but so long as the vehicles are self-powered and move on rubber-tired wheels, no significant changes in their configurations or their descriptive characteristics are anticipated.

The possibilities for control are quite another matter. The research agency has been preoccupied with automated traffic and vehicle control. Most of the more advanced control techniques have been investigated in connection with high-speed ground transportation system concepts such as the Urbmobile, Teletrans, Commucar, Glideway, StaRRcar, and the Century Expressway. However, past and current projects sponsored by the Highway Research Board (NCHRP Project 3-2) and the Bureau of Public Roads (Contract No. CPR 11-2856) have shown the desirability of adapting some of the techniques for traffic control on streets and highways. Implementation of such controls could permit a significant reduction in the numbers of control, advisory, and information signs and markers alongside the highways (audio, instead of visual, communication).

Control for assignment of right-of-way may continue as currently used; that is, the visible control on the street may remain essentially unchanged. This would include standard, three-color traffic signals, directional turn arrows, flashers, and pedestrian signals. But the manner of establishing warrants for installation of these devices, as well as the determination of control settings, may vary widely from current practice. A specific example is cited here.

There is a high probability that traffic movements in densely traveled areas will be controlled by real-time surveillance and decision computing equipment. A significant alleviation of the surveillance problem could be accomplished by cooperation on the parts of the vehicles. As of now, all surveillance is performed by detector equipment that has no dependence on any active (cooperative *) signal from the vehicle. If each vehicle were to be equipped with a low-power beacon that radiated a characteristic tone for the type of vehicle, the problem of detection and classification of vehicles would become nearly trivial. Low-cost microwave oscillators could be placed on the vehicles that would radiate a very narrow beam, so that counting accuracy of vehicle position could permit a level of traffic control that is much more precise than is in general use today. This precision would stem from the use of general-purpose, high-speed digital computers into which control logics and algorithms for decisions could be programmed that could use to advantage the information provided by the identifier beacons.

It would be expected, therefore, that the incorporation of new capability into vehicle-assisted traffic surveillance and control equipment may call for revisions to the *Manual on Uniform Traffic Control Devices for Streets and Highways.* For one thing, the warrants can be changed. As more sophisticated equipment is made available, the safety that accrues from positive assignment of right-of-way will be sufficient reason for the installation of signals at presently uncontrolled or stop-controlled intersections. The *Manual* points out that fixed-cycle signal equipment can generate, rather than reduce, accident causation, when traffic-insensitive controls are applied at points of low volumes. It appears that the frustration of being stopped for no substantial reason breeds a contempt for the signal that far outweighs the good that the signal does at the rare times when a crossing interference does occur. Subsequent running of the signal can result in catastrophe.

Another evolutionary revision to traffic behavior is expected to stem from the entire changing attitude of the Federal Government toward the problems of transportation. It might be expected that a controlling body, similar to the Federal Aviation Administration, will be created that will establish specifications for all design, material, manufacture, and maintenance items that are in the public interest where safety is the issue. One of the items that surely must come under control is the configuration, location, and intensity of the rear lights on a vehicle, including those that indicate change of speed.

* In discussing this feature, the language of space technology is used since there is no similar situation in a discipline more closely related to traffic engineering. A non-cooperative system is one in which the surveillance equipment must radiate energy that will be reflected by the target so that an unambiguous signal will be returned to the detector. A cooperative system is one in which the target either radiates a signature continuously or responds on interrogation by the search radar (or other seeker).

Because of the completely undisciplined manner in which taillights are designed at present, for style rather than for function, the following driver is denied their use for estimating distance between vehicles and the number and relative lateral locations of two or more vehicles in a group ahead. It is not expected that an arrangement such as the port, starboard, and stern position (navigation) lights, common to aircraft and marine use, would be appropriate for vehicles. Rather, an unbroken horizontal stripe, of specified uniform length, of red illumination should be displayed in the lower portion of the rear of each vehicle, regardless of the vehicle size. Thus, the visual arc intercept could be used by a trailing driver to gauge distance and lateral placement of vehicles ahead, as shown in Figure 10. The change in traffic flow because of such standardization is not expected to be discernible, but it is believed that greater safety will result.

Changes in car-following behavior, as reported by Herman and Rothery (*25*), indicate that increases in highway capacity may be expected if improved speed-change signaling systems are installed. Such installations may be a subject of regulation by a Federal agency. A two- or three-color signaling system that will take its information from a change in engine manifold pressure may be feasible. By using an adequate step in pressure change, either positive or negative, "noisy" throttle operation by a lead driver can be masked out, and only signals for significant speed changes would be transmitted. This improvement in early warning of lead-driver intention tends to entice the following driver to hold a closer headway at a given speed, resulting in increased volume for each lane.

Thus, the use of engine-manifold-pressure-actuated speed-change signal lights, preferably located high on the rear of a vehicle, may be expected to yield increases in lane capacities, a change that should be reflected in the *Highway Capacity Manual.*

ADDITIONAL CONSIDERATIONS—GEOMETRICS AND OPERATIONS

Headlight Sight Distance

The effect of headlight illumination on the degree of vertical curvature is discussed in the AASHO *Policy* of 1965, but there seems to be no specification of required illumination intensity. Illumination intensities are specified for various classes of roads and streets, in Table 16.8 of the *Traffic Engineering Handbook,* for normal street-lighting systems.

It is recommended that specific values of headlamp illu-

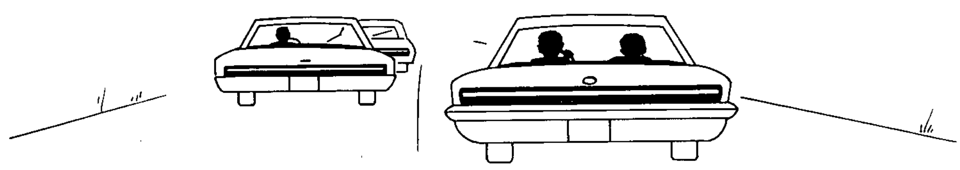


Figure 10. Uniform rear light design.

mination intensity for sight distances be used on otherwise unlighted highways. Such a specification would apply to both vertical and horizontal curvature of the highway. It may be that the illumination intensities given in Table 16.8 would be adequate for this use. The use of an arbitrary headlamp height, and angle from the beam, to compute sight distance on sag curves should be discontinued in favor of a specified illumination intensity from the beam pattern. By the establishment of such a standard, the highway designers would secure their own guidelines and, at the same time, furnish a constraint on the arbitrary changing of headlamp characteristics by vehicle designers.

Methods for testing for and computing headlight sight distances are shown in Appendix A.

Cruising Sight Distance

There is no specification of a sight distance that will ensure that motorists can maintain running speed on a highway without necessity for a stop of the severity of that defined previously for stopping sight distance. Motorists will not maintain a desired running speed (much less the design speed) if obstructions to vision occur at high frequency, even if stopping sight distance always is provided.

The reason is fairly obvious. A stop according to the formula for stopping sight distance occurs at a much higher acceleration than is judged to be comfortable. Thus, it should not be expected that drivers would maintain a speed on a highway that frequently required them to be on the alert for an urgent stop. Such a highway might be safe to drive at the expected running speed, but it would be exhausting.

Therefore, a cruising sight distance should be used—one that would be determined from a more leisurely reaction time than the 2.5 sec used in computing stopping sight distance. Deceleration would be much lower also, somewhat in keeping with the representative leisurely rate to reduce to zero speed, as shown in Figure VII-16 of the AASHO *Policy* of 1954. This cruising sight distance would be required for the major portion of the highway or, conversely stated, a condition in which sight distance is restricted to less than this value should not be permitted to occur at greater than a stipulated frequency.

Determining a criterion for this frequency does not appear to be an easy matter. The design characteristics of the vehicle enter into this criterion in a very minor way. Primarily, the desires and ease of mind of the drivers will be the controlling factors. A numerical evaluation of how these factors will be affected by reduced sight distances might be derived by observations of running speeds on winding and undulating roads. The sight distances would be tabulated for various sections at which it was restricted, and the approach speeds observed by means of a time trap. Better resolution of the speed profile would be obtained by reading vehicle speeds at three points: the first well upstream of the sight restriction, the second where sight distance was minimum, and the third a short distance beyond the point where unrestricted sight distance was again restored.

Sight distance for a leisurely stop could be determined quite reasonably from a study of the speed profiles of vehicles approaching an intersection at which a mandatory stop signal is installed. Such a study is being conducted by the research agency under the sponsorship of the Bureau of Public Roads (*21*).

Setting of the Amber Phase in a Traffic Signal

It has been noted that the treatment of stopping sight distances in the AASHO *Policy* of both 1954 and 1965 carefully takes into account values for driver reaction times and vehicle decelerations from various speeds. However, this attention to detail has been omitted in the *Manual on Uniform Traffic Control Devices for Streets and Highways* where the length of the amber phase in traffic control signals is discussed.

Because the amber phase constitutes a notice of probable need for a stop, it should be sufficiently long to allow adequate stopping distance for the critically located vehicle, for the posted speed limit on the approach to the signal. Actually, the length of the amber phase should include consideration of the grade on the approach, a downgrade requiring a longer warning period than an upgrade. The expression for the length of the amber phase can be developed from that for stopping sight distance, which is given in the *Traffic Engineering Handbook,* Eq. 17 (p. 28), as:

$$S_d = 1.47Vt + \frac{V^2}{30\,(f \pm g)} \qquad (7)$$

The minimum required length of the amber phase of a traffic signal can be derived from this expression, as follows:

It is assumed that a certain speed limit, V, is posted for the approaches to an intersection. Also, that in keeping with the AASHO *Policy* for stopping sight distance, a value for deceleration inertia factor, f (equivalent to limiting tire-to-road friction coefficient), is specified as not to be exceeded. Then, as a vehicle approaches the intersection, it can be randomly located at the time the signal turns amber. Because it is assumed to be traveling at speed V, it will not be able to stop unless it is at least S_d from the intersection. Therefore, a vehicle within S_d of the intersection should continue through at V, and the length of the amber phase should be sufficient to provide clearance. Neglecting the width of the intersection, the minimum length of the amber phase, t_a, should be:

$$t_a = \frac{S_d}{V} \qquad (8)$$

It will be noted that the use of a minimum amber phase stipulates that there is a single critical location for a choice on what to do when the signal turns amber. If a vehicle has not yet reached S_d, it must indicate a stop, because there will be insufficient time at speed V to clear the intersection before the signal will have turned red. And, as shown previously, if it is closer to the intersection than S_d, it cannot come to a stop without exceeding f.

In practice, it may be desirable to provide a small additional time to the amber phase to act as an intersection clearance interval. Between this and some vehicles that will exceed V through the intersection, there will be a region of choice on whether to stop when the signal turns amber. But in no case should the amber phase be less than t_a in Eq. 8.

Critical Location Marker

In the discussion on the setting of the amber phase in a traffic signal it was mentioned that there can be a critical location for a vehicle on the approach to the signal. If the vehicle is approaching at the speed for which the amber phase was computed, this location will be the decision point for subsequent action. If the signal turns amber when the vehicle is past the critical point, the driver should not attempt to stop, because in doing so he would have to exceed the deceleration level prescribed for such stops. If the vehicle is not yet arrived at the critical point, the driver should initiate a stop, otherwise the vehicle will enter the intersection after the signal has turned red.

It is obvious that an experienced driver can acquire judgment as to what constitutes critical location for various approach speeds. But it appears that it would be useful to include, in the design of the markings of a highway, an indication of the location of the critical point, especially on rural roads where high approach speeds prevail. The marker might be either a yellow disc painted on the pavement or a yellow disc mounted on a sign standard at the side of the road. Because its application would be universal, no explanatory legend would be required.

Design of Horizontal Curves

The geometrical properties of a curving roadway can be described by the following parameters (assuming that the center line of the road lies in a flat plane and that the crown is negligible):

1. Radius of curvature.
2. Rate of change of radius of curvature, as a function of distance along the curve.
3. Superelevation (bank angle).
4. Rate of change of superelevation as a function of distance along the curve.

There are a number of considerations, stemming from both the vehicle and the driver, that will affect the selection of values for the listed parameters. The interplay of these considerations is discussed, after which some conclusions are drawn as to future design procedures.

The AASHO *Policy* gives the following expression for "minimum safe radius" of curvature:

$$R = \frac{V^2}{15\,(e + f)} \qquad (9)$$

in which

V = vehicle speed, mph
e = superelevation (tangent of the bank angle)
f = limiting side friction factor
R = radius of curvature, feet

It is reasonable to assume that any curve will be designed so that some speed, V (design, running, or other), will be held constant throughout its length. Therefore, one consideration that must bound the value for radius of curvature is the resultant acceleration factor, n, expressed by:

$$n = \sqrt{\frac{V^2}{gR} + 1} \qquad (10)$$

in which

V = speed, feet per second
R = radius of curvature, feet
g = gravitational constant

The limiting value for n is not likely to be set by a vehicle characteristic, but is much more apt to be a tolerance limit expressed by the passengers of a vehicle. Further, because the resultant acceleration is not likely to be normal to the pavement, the degree of side acceleration felt by the passengers (or the overturn moment in a cargo vehicle with a high C.G.-to-tread-width ratio) will have a strong modifying effect on n.

Then, if n is further broken into its components by:

$$n = \sqrt{n_n^2 + n_s^2} \qquad (11)$$

in which

n_n = normal force factor
n_s = side force factor

one limitation on R may be stated as follows:

$$R = \frac{V^2}{g\,(n^2 - 1)}$$

Intuitively, because side acceleration will be less tolerable than normal acceleration, the larger the value of n_s, the smaller will be n, giving rise to larger values of R.

The conclusion that the resultant acceleration is not likely to be normal to the pavement derives from the fact that airplane passengers usually are unaffected by the increased load factor in a 30° banked turn ($n = 1.15$). It is doubtful that a highway engineer would build a road with a 30° superelevation. Therefore, a steady-state minimum radius of curvature must be designed by some practical value for e and an acceptable value for n_s. Thus, if e is restricted to small angles, the AASHO expression may be written as:

$$R = \frac{V^2}{15\,(e + n_s)}$$

in which it will be understood that n_s is less than or equal to the side acceleration factor accepted by people, or is less than or equal to the limiting side friction coefficient, f, whichever is smaller.

There appears not to be any specification for maximum radius of curvature, although there seems to be a logical reason for so doing, and it is hardly academic. In general, vehicles are designed with a positive margin of static stability (they track straight unless disturbed) because of the caster angle built into the steering system. Therefore, such a vehicle, traveling a straight, uncrowned road, should require no steering inputs by the driver, except to correct disturbances created by road anomalies.

Now, if this vehicle is driven around a curve, if the radius of curvature is sufficiently large, the steering input required to hold the curve may be so small that no feedback to the steering wheel will be felt by the driver. Therefore, the driver usually will actuate the front wheels sufficiently to have the steering system move out of the dead zone. In effect, the driver has overcontrolled, and must make a subsequent correction. The result is that the curve is negotiated by a series of steering torque reversals, which does not make for accurate control. (Power-augmented steering systems tend to aggravate this situation.)

The solution to this problem, which derives from the handling characteristics of the vehicle, lies in stipulating some maximum value for *R*, so that the turning maneuver is accomplished by a steering torque that remains in the same direction. Corrections to the path would be made by variation of manual force, without change of sense.*

Obtaining a value for R_{max} may be done by either of two methods. The first would be by driving a vehicle, or assorted vehicles, over a series of curves of decreasing radius of curvature. If a single vehicle is used, it should have a variable ratio, variable feedback steering system, so that all types of vehicle steering characteristics may be simulated. If a number of vehicles are used, their steering characteristics should span the major portion of the range of characteristics for all on-highway vehicles.

The second method would be to use a driving simulator that was equipped to provide variable ratio and feedback. (Such a simulator has been developed by the research agency.) It might be argued that some realism might be lost due to elimination of kinesthetic sense of lateral acceleration, but the argument cannot be a strong one. The lateral acceleration, if it was not removed entirely by superelevation, would be small to the degree of being below or barely within the driver's threshold of sensing the lateral acceleration.

The final matter to be considered, in the design of horizontal curves, is the transition from the tangent portion. The transition may be either an entry into an arc of constant radius of curvature or immediately into a recovery back to a tangent. If the design of the highway includes a superelevation, then entry into the curve will produce not only a lateral acceleration caused by radial acceleration, but a superimposed lateral acceleration because of roll of the vehicle, as well.

Having examined the typical lateral acceleration † values used in highway design, as represented by the AASHO *Policy* of 1965, and the history of the development of current practice, there seems no reason to suggest any change. The use of the spiral curve for transition is, of course, the most logical choice, from the point of view of human factors. Any modifications to present practice that might result from exhaustive tests of drivers performing the transition task would be lost in the variability of the manner of performing the task, caused by differences in drivers, vehicles, surface conditions, and meteorological environment. The values of lateral acceleration factor, shown in Figure III-4 of the *Policy*, vary from 0.16 to 0.11, depending on speed. The tests that indicated discomfort thresholds varying from 0.21 to 0.15 were for steady-state conditions. The build-up of the acceleration factor to these limits would take upwards of 8 sec for the recommended lengths of transition curves. Therefore, the rate of change of radial acceleration would be well below that determined from flight tests in which the tolerable limit was less than 0.08 g at 3 to 4 cps (*26*).

To summarize, it is suggested that a maximum radius of curvature be established that will reduce the tendency toward hunting due to over-control. The rest of the design procedures should remain as they are.

Superelevation

The past practice has, to a great extent, been to limit the superelevation angle (in northern latitudes) so that a stopped vehicle would not slide sideward if the road surface was covered with glare ice.

This would appear to be an overly conservative view. Such a vehicle could do no more than slide onto a horizontal shoulder. Against the very low probability of such an occurrence (the glare ice and the stopped vehicle) there is the very high probability that vehicles entering a banked curve of such restricted superelevation might, even at seemingly reasonable speeds, exceed the lateral friction factor, with subsequent loss of control. It should be obvious as to which is the more dangerous situation.

The procedure for calculating radius of turn, which includes consideration of superelevation, has been discussed. It is concluded that the method is correct. However, the values that are used as limits for superelevation and, more particularly, the underlying philosophy behind the adoption of these values may be questionable.

A more rational approach would be to minimize the risk of loss of control for the case of typical speed on an icy surface. This should be the average speed for vehicle operation on a straight section of road having the same grade as the curve. The angle of bank should be computed that results in zero lateral acceleration (resultant normal to the road surface) and the superelevation made to agree with this angle.

Current design usually limits the value of *e* to 0.10 (up to 0.12). This is equivalent to a lateral force factor of 0.10. The same design practice suggests the use of lateral force factors (from radial acceleration) varying from 0.16 to 0.11, depending on speed, the higher value being used at lower speed (30 mph). In order for the 0.10 friction factor for ice not to be exceeded, the low speed would have to be reduced as computed in the following manner.

Using the expression from the AASHO *Policy*,

$$R = \frac{V^2}{15\,(e + f)} \qquad (12)$$

the radius of turn for the 30 mph case is computed to be 230 ft. For $f\,(n_s)$ not to exceed 0.10, the speed would be reduced to 26.3 mph. If no lateral force is to be encoun-

* The analogous situation occurs in flight. It is more difficult to execute a turning maneuver with a very shallow bank angle than it is to make a medium-banked turn. These types of determinations have been made by the CAL Flight Research Department, using highly-instrumented, variable stability and control characteristics airplanes.

† The term "lateral acceleration" or "lateral acceleration factor" is used in preference to "side friction factor." The implication of the word "acceleration" is just that. It is a dynamic condition that is being experienced, whereas the "friction" in a term normally is accepted as implying the limiting coefficient that is available before skidding occurs.

tered, the speed would be further reduced to 18.6 mph. It should be substantiated that such a disparity exists between the nominal speed for such a geometric design and the speed that must be maintained for minimum control perturbation. If the drivers do not slow down of their own volition, the design standards should be changed to suit existing conditions.

Night Vision—Wet Weather

Wet weather causes a drastic reduction in visibility from vehicles, especially at night. Part of the deterioration of driver vision is caused by the uneven film of water on the windshield (both inside and outside) and part by the manner of illumination of the highway by the vehicle's headlamps. The ensuing discussion deals with that portion of the problem that is within the highway designer's province. Clearing and defrosting the glass is solely the problem of the vehicle manufacturer.

First, consider the case where the roadway ahead is illuminated only by the headlamps of the vehicle in which the driver is located. It is immediately apparent that the wet surfaces offer a specular reflection, instead of the diffuse return that occurs when the surfaces are dry. As a result, the amount of the return is greatly reduced, and is restricted only to those surfaces at the proper angle of incidence (the rest of the light is scattered away from the driver's eye). The result of this physical phenomenon is well known—pedestrians in dark clothes are struck, vehicles run off the road, exits from freeways are difficult to follow, etc.

The highway engineer has no control over much of the environment adjacent to the highway, certainly not over the dress or behavior of pedestrians. But it may be possible to increase the reflection from the roadway, which would yield much-improved silhouetting of objects on the road and better delineation of the paved surface. At the present time there seem to be no specifications that encompass the subject of road surface treatment for reflectivity. It is suggested that the feasibility of increasing diffuse reflectivity of wet surfaces be investigated and, if successful solutions are found, appropriate specifications be established. Some improvement may result from directional texturing of the paved surface and, perhaps, subsequent directional spraying with white or light-colored paint, to increase the reflectivity of the near side of the asperities.

A different situation occurs when the headlights of opposing vehicles illuminate the highway. It is not clear that anything, other than reduction of the specular return from the road surface, is within the province of the highway designer. Direct glare is a matter of vehicle design.

Finally, lighting external to the vehicle is a highway design consideration, but it appears to be a topic that can be treated independently of vehicle design. This assumes that future windshield design will be no worse than it is today, where the extreme angles of slope cause "double" image sources to appear at night, even though the second image is of low intensity.

Determination of Lane Width

The procedure used to obtain data from which to specify lane widths was to observe the behavior of drivers of commercial vehicles when passing in opposing directions on two-lane rural highways (*5*). Both clearances between vehicles and use of the shoulder were used as criteria, a judgment being made on the safety of operation versus clearance or margin.

It is not at all obvious that this procedure for determination of lane width is either critical or optimally appropriate. The division of attention, between tracking in the lane and observing the oncoming vehicle, does not constitute a difficult task for the driver. Further, the critical period during which accurate guidance is required is of short duration. It is true that any combined error on the parts of the drivers that leads to a collision course can have catastrophic results, so a positive clearance is of paramount importance.

It is possible that the requirements for guidance of commercial vehicles passing in the same direction should have some bearing on lane-width determination. This is an opinion, based on the impressions of a number of research agency technical and non-technical, male and female personnel who were queried on the two passing maneuvers. Only 6 of 31 persons thought that the opposing traffic situation required greater effort or was more unnerving. It would appear that some thought should be given to evaluating the method for establishing lane widths, in the light of at least one alternative procedure.

DATA ON VEHICLE CHARACTERISTICS

One of the objectives of this project was to investigate current data and existing sources of information to determine the data that are available and useable concerning the necessary vehicle characteristics, and to collate and prepare a digest of these data.

It is not possible, within the scope of this project, to collect all values for all parameters contributing to the characteristics of the vehicles that can affect highway design. Even if it were done, the values, because many vary widely from each other, would be meaningless without application of some logic or philosophy to weigh their relative importance. The latter clearly is not within the province of this project.

Initially, this may sound contradictory, in view of the fact that some definite recommendations have been made concerning the use of some numerical values. Those recommendations were made either where it was felt that a clear engineering rationale could be shown or where their adoption would not exclude any part of the vehicle or driver population. For instance, the discussion on superelevation suggests an approach which would minimize tendency toward loss of control on slippery pavements, so that the final measure of effectiveness would be least loss of life, property, and transportation performance. By contrast, it might be suggested that heights of overpass structures be established so that some optimum compromise be achieved between cost of construction and re-routing of too-high vehicles. To adopt such a standard would exclude non-conforming vehicles, a decision that would be much more political than economical.

Returning to the subject of specific numbers, it would be possible (but not within the scope of this project) to list the lengths of all passenger vehicles on the U.S. highways—but to what purpose? Only if the maximum or minimum dimension was a controlling feature would this be sufficient. If some statistical property of the population of these vehicles was meaningful for design, some decision would have to be made on how to weight the various dimensions within the population. Clearly, the numbers themselves are secondary to the needs of this project; the primary need is the source file.

The most complete single file on the physical (and some performance) characteristics of U.S.-built passenger vehicles is to be found in the *"AMA Specifications—Passenger Car,"* which are maintained by the Automobile Manufacturers' Association.

The data listed in the AMA specifications are directly applicable to determining the following characteristics for passenger vehicles:

- Over-all dimensions
- Turning radius
- Wheel suspension characteristics
- Headlight illumination
- Longitudinal center of gravity position
- Tire outside diameter
- Stoplight position.

The Automobile Manufacturers' Association has also published *Parking Dimensions—1969 Model Cars,* which includes information relative to height of door opening and vehicle underclearance and end clearance.

The counterpart of these specifications does not exist for commercial vehicles (trucks and buses). Scant data are published in *Automotive Industries* and *Commercial Car Journal,* but complete information would be available only from the manufacturers. In a discussion with personnel of the Chilton Company, publishers of the two trade journals mentioned (*27*), it was determined that almost any vehicle over 20,000-lb gross weight would be custom built. In general, where the very large vehicles are concerned, the vehicle specifications will be constrained within limits established by the applicable state highway regulations in the regions where the vehicles are to operate.

A useful source for general information on vehicle operating characteristics is Chapter 2, of the 1965 edition of the *Traffic Engineering Handbook.* Some of the data are not current, but would be applicable. Information appropriate to the following characteristics is available:

- Over-all dimensions
- Maximum allowable (legal) gross weight
- Turning radius
- Acceleration capability vs speed
- Deceleration capability vs speed
- Tire coefficient of friction on various surfaces
- Vehicle underclearance and end clearance.

All of the data shown, except for some physical relationships on motion, are extracted from other documents, and these references are given.

The widely used SAE *Handbook* is actually a compendium of materials specifications, hardware design standards, testing procedures, etc. The one vehicle characteristic that is included is the illumination beam pattern for sealed-beam headlights.

CHAPTER THREE

INTERPRETATION, APPRAISAL AND APPLICATION

The findings of Chapter Two are of a heterogeneous nature, as related to the problem of how the vehicle interacts with the highway. Much of the variability of the findings stems from the fact that subjective judgments and actions on the parts of the driver population are used to modify the maximum capabilities of performance of the vehicles. Other variations are due to the great range of characteristics of the vehicles themselves. Still others are due to the fact that the highways differ in geometry, surface conditions, and environment.

Certainly it would seem that any action resulting from the findings should be applied uniformly, for the sake of consistency. Although such uniformity of design standards for the entire United States may be desirable, it is unwarranted in some instances. ("Design standards," as used here, applies to all three of the related elements—the highway, traffic operational procedures, and the vehicles.)

Some of the practices and standards can be sectional in character, primarily because of topographical and climatological differences across the face of the nation. For instance, traffic on the highways of one of the states of the Great Plains would be much less affected by differences in power-to-weight ratios for commercial vehicles than would traffic in mountainous country. Similarly, the current practice of limiting superelevation to be compatible with side-sliding friction coefficients on icy surfaces is inconsistent with conditions in some sub-tropical states.

Generally speaking, the findings indicate that the major portion of the practices and standards that have been developed over the years for highway design and traffic operations are valid, and should continue to be used. The findings can be classified for three avenues of action. In the first of the three, analytical (explicit numerical) and empirical (both numerical and subjective) relationships between the highway and traffic operations and vehicle design have been examined and it is recommended that present practice be continued. There is no evidence that a change is warranted.

In the second case, some subjective relationships that were examined were found to be either improperly or not at all recognized in present practice. Here,, recommendations have been made for new or improved procedures to relate the vehicle to the highway/operations. The third avenue of action has to do with those relationships in which subjectivity plays a negligible or no part, wherein the analytical investigation results in recommendations for new or improved practice. The specific recommendations for modifications to standards or investigations into the need for modification are shown as part of the findings (Chapter Two). These items also are listed, under the previously described classifications, in Chapter Five, Suggested Research.

It is expected that agencies responsible for, or interested in, the implementation of standards of practice will review the findings and recommendations. Then, acting with the same purpose that prompted the formulation of the project statement, they should pass on the recommendations. Those selected for further action should be implemented, as required, by a change in standard, or the procedure for determining a standard, or an investigation leading to changes in values in a standard. As used here, the word "standard" can apply to the highway, traffic operations, or vehicle design.

Certainly significant benefits in the total operation of the highway system should result from consistent, compatible, rational design and control standards and driver-use doctrines. To whatever degree the findings of this investigation can help to improve these standards and doctrines, appropriate benefits should accrue.

This investigation showed that the greatest disparities in the driver-vehicle-highway control system occur in the driver and vehicle characteristics. If truly significant gains in the performance of the system are to be made, the reduction of driver-vehicle variability will produce the most dramatic changes. (In the present context, the word "performance" takes on a most comprehensive meaning. It includes safety, cost, comfort, and convenience, as well as the more usual measures of traffic volume and travel time.) Perhaps the greatest single contribution of the study is the conclusion that the drivers and the vehicle characteristics —rather than the highway designer and the traffic operations engineer—are responsible for many of the problems associated with highway travel.

This study began with a review of those documents that are regarded and accepted as national (and international) standards, with some local exceptions. In addition, the highway design manuals for several typical states were examined. Most of the findings and recommendations resulting from the investigation apply specifically to these documents. The exceptions are those instances where standardization or modification should be incumbent on vehicle manufacturers or driver-licensing agencies. Examples of requirements on the vehicle manufacturer might be height of headlights and field of vision from a specified height of the driver's eyes. A standard to be implemented by a licensing agency would be to check that obviously short drivers would modify their seating so that they meet the specifications for height of the driver's eyes.

APPLICATION

The results of this investigation may be of interest to nearly all engineering and administrative personnel who are concerned with highway design and traffic operations. Direct application of the findings, however, is confined to the purview of relatively few individuals and an even smaller number of documents.

As noted, the starting point for the study was several documents that were reviewed for standards affected by vehicle characteristics. The findings of the study have application to these documents, and not much else, and therefore are of most direct interest to the people who are responsible for promulgation of the standards and procedures for which changes are suggested.

Of course, if the recommendations of this study result in changes to the standards and procedures, then the final application of the investigation will be to the general motoring public.

CHAPTER FOUR

CONCLUSIONS

Within the scope of the investigation, and from the perspective that was adopted (permanence of the highway vs temporal nature of vehicles), the following general conclusions have been drawn:

1. Most highway design features and traffic operations procedures, that relate to vehicle characteristics, are governed by standards that are satisfactory in their present forms.

2. Several procedures for design and operations should be modified.

3. Investigations should be initiated to determine whether the existing standards for several other design practices should be modified.

4. There appears to be justification for the adoption of some new practices.

Because these conclusions cover a multiplicity of items, they are listed separately in Chapter Five.

The detailed investigation of how vehicle design characteristics related to highway geometrics underscored the need for stabilizing the vehicle characteristics. The highway designer's standards should not be revised just to accommodate the often arbitrary and unpredictable changes in vehicle characteristics made by the manufacturers. Therefore, an unlooked-for conclusion is that some vehicle design standards should be imposed on the industry and, for the sake of uniformity, probably by some agency of the Federal Government. Typical of such standards might be the configuration and location of lights, both front and rear, illumination and communication. A program should be established to review vehicle characteristics to determine which ones are amenable to being standardized.

CHAPTER FIVE

SUGGESTED RESEARCH

The items on which action is recommended fall into two general classifications. These items are listed here, under the two classifications, and each is discussed briefly.

No attempt has been made to refer to the documents, and the locations within these documents, in which the subject for the research is treated. For one thing, the source material may appear in more than one place (and there are no guarantees that all will be found). For another, and more important reason, it is felt that the persons who have particular interest in the recommendations of this report are completely conversant with the contents of the documents and can go directly to the source material without assistance from a reference list.

One general comment is offered, particularly concerning the use of the two AASHO *Policies* that were reviewed for Chapter Two. Practically all of the design standards shown in these volumes are minimums—boundary values that separate acceptable from not-recommended practice. Emphatically, the liberal use of these minimums as design standards leads to only marginally satisfactory highways, with less-than-expected running speeds, and higher-than-average accident rates. Highway designers should use minimum standards only when they are unavoidable, and should try to incorporate practices that lead to more tolerable or desired geometric features and controls, where feasible.

DESIGN AND OPERATING RECOMMENDATIONS—SUBJECTIVELY DETERMINED

1. *Maximum Rates of Curvature.*—Ball-bank indicators, which are insensitive to body roll angle, have been used to determine lateral acceleration limits. It is expected that the larger the roll angle, the lower will be the lateral load factor comfort limit. Tests should be conducted to note the effect of variation of body roll angle.

2. *Transition Curves.*—The use of spirals would be preferable to laying out compound curves. Determinations of how well drivers will track the nominal path of the two types of curves should be made, either by use of high-angle (or vertical) photography, or by use of a driving simulator.

3. *Medians.*—For narrow medians, further examination into screening against headlight glare is suggested.

4. *Cruising Sight Distance.*—The difference between a safe speed of operation and a realized running speed over a segment of roadway may derive from driver tension incurred in remaining just within the safe limits. Thus, a road designed with stopping sight distances for a given speed will not induce drivers to maintain that speed if the minimum stopping sight distance appears too often. A desired running speed will be attained only under more relaxed driving conditions, and a cruising sight distance consistent with this running speed should be specified. An investigation into cruising sight distance design standards should be made.

5. *Design of Horizontal Curves.*—Minimum radii of curvature are shown but no maximums are suggested in current design practice. It is possible that rates of curvature should be high enough so that the null region of steering will be exceeded by a satisfactory threshold for feedback. Tests should be conducted to determine the effect of rate of curvature on steering reversals (and tracking accuracy), using vehicles that will give representation over the available range of steering characteristics.

DESIGN AND OPERATING RECOMMENDATIONS—EMPIRICALLY AND ANALYTICALLY DETERMINED

1. *Superelevation.*—Present design philosophy might be changed to give better security against skidding on ice-covered curves, for those vehicles operating at characteristic speed on those curves. Observational studies of characteristic speeds of vehicles on icy roads should be made.

2. *Lane Width.*—Desired value has been determined from observation of driver-vehicle behavior for large commercial vehicles. So far, the passing maneuvers in opposing directions on two-lane highways have been the sole basis for this empirically determined value; this, of course, does not relate to divided highways. It is suggested that lateral clearance between vehicles in the overtaking and passing maneuver be investigated. This applies to both straight and turning roadways. Additional testing for lane-width requirements should include some consideration of wide loads (house trailers etc.) under various conditions of tracking stability. See "Handling Quality," which follows.

3. *Medians.*—For wide medians, additional attention might be paid to lateral travel of vehicles leaving the pavement, for any of a number of reasons, so that a reasonably low probability exists that the vehicles will cross into the opposing lanes. A file of data on trajectories of vehicles entering open medians should be developed so that adequate widths can be specified.

4. *Field of Vision.*—Downvision over the nose of vehicles should be measured, particularly to the line extended forward through front and rear wheels on the right-hand side. This information, coupled with driving tests on lateral location in a lane, should indicate the effect of downvision on lane-width requirements. Specifically, typical clearances between moving and parked vehicles (or other roadside obstacles) and between vehicles moving in the same direction should be measured.

5. *Natural Frequency—Front and Rear Suspensions.*—It is suggested that a specification be set on the amount a surface profile may deteriorate (such as corrugation of asphalt due to creep) before repairs are effected. This will limit the excitation that the surface can provoke in a vehicle's wheel suspensions. The specification should contain maximum permissible values on frequency-amplitude combinations. Frequency can be converted to wave length by using perhaps 120 percent of the posted speed limit as the design speed. Amplitude would be depth between peaks.

To arrive at representative limits for excitation, the natural frequency of the spectrum of vehicle wheel suspensions must be known. The limiting amplitude at these frequencies also is required if they are not to exceed the capability of the damping equipment (shock absorbers) to prevent diverging resonant oscillations.

The specifications suggested would be applicable to procedures to be followed primarily by highway maintenance personnel, less by highway designers.

6. *Natural Frequency—Sprung Mass.*—It is recommended that a specification be set on road vertical profile that will limit the excitation that the surface can generate to oscillate the vehicle sprung mass in both vertical and pitching modes. The procedure would be similar to that discussed, except that the natural, damped frequency of the sprung mass would set the limits on wave length and depth.

This specification might be most applicable for road construction procedural or inspection handbooks.

7. *Headlight Sight Distance.*—Some recent models of passenger cars use an over-and-under disposition of headlights, with the high beams beneath. If current aiming practice is used, these vehicles are penalized on sight distance on crest vertical curves in rural areas (high beams should not be used in urban driving).

The distance penalties might be measured and the public and the auto manufacturers informed. If the current trend becomes prevalent, design standards should be reviewed and existing construction posted for lower speeds at night.

8. *Shoulders.*—Widths of shoulders have reflected requirements for vehicles to seek refuge, leaving a 2-ft clearance between the vehicle and the right-hand margin of the near lane. It is suggested that the width might also take into account the behavior of the drivers in establishing clearance for a parked car, while passing it at running speed. In the absence of adequate clearance, either a lateral displacement in the lane should be expected of the passing vehicle, or it may reduce speed. It may be of interest to study the behavior of passing vehicles, but it is not essential.

9. *Curbs.*—The face of barrier curbs should be of suitable material that does not produce a high coefficient of friction when in contact with the sidewall of a typical pneumatic tire. This should reduce the tendency of an encroaching vehicle to climb the barrier, and lead to less loss of control on the rebound.

10. *Guide Posts.*—Standards should be adopted for the use of guide posts. As delineators, they should be only sturdy enough to carry whatever reflective marker is usually applied. Concrete, or similar, guide posts often inflict more damage to a vehicle and its occupants than might have been sustained if the post had not been impacted. Where separation from roadside hazards is required, guardrails should be installed.

11. *Running Speed.*—For consistent highway design, the use of running speed, as an occasional substitute for design speed, should be discontinued.

12. *Guardrails.*—Performance and application of guardrails and their location with respect to the road should be standardized across the nation. A recommended policy is that strength and stiffness of both rails and supports should reflect minimum damage and/or loss to motorists, on a statistical basis. (An optimal design for commercial vehicles will not be optimal for passenger vehicles, so that frequencies of impacts must be considered.) Guardrails must be used with judicious precaution; their presence must lead to less total loss than the consequences of not having them in place.

13. *Height of Center of Gravity.*—Guardrail design should be affected by overturn moments on vehicles striking at oblique angles. Overturn moments will be a function of height of the center of gravity of vehicles and will be most critical in the case of loaded commercial vehicles. Estimates of probable C.G. heights should be made for typically loaded commercial vehicles.

14. *Tire Outside Diameter.*—Some better control of road maintenance requirements is recommended than the practice of repairing the roads that seem to need it most, to the limit of the budget. A specification should be set on the limiting depth for various diameters of holes in the pavement. These values probably would derive from the combination of smaller wheel diameters and less responsive handling qualities. Criteria for limiting damage to vehicle wheel suspensions and tires and for preventing loss of control should be established, for which wheel diameter would be a governing factor. Tests of vehicles on damaged roads will be required.

15. *Handling Quality.*—This characteristic of a vehicle is the result of many contributing factors, not the least of which is the behavior of the human in the combination.

The importance of handling quality is apparent in determining lane widths, cross slope, lengths of weaving sections, and road surface profile conditions. At best, the problem of quantifying this characteristic will be difficult and will require many tests, for the results can be derived only from statistical tests of the driver-vehicle-highway-environment combination. Considering the time that has elapsed since tests were last performed to determine lane widths, and the significant changes that have occurred in steering systems in that period, it is recommended that new and exhaustive tests be conducted on handling qualities. Particular attention should be paid to tracking accuracy on straight and curving roadways.

16. *Amber Phase in a Traffic Signal.*—The setting of the amber phase should be made consistent with the times derived from stopping sight distance for various approach speeds. By so doing, the AASHO *Policy* for 1965 and the *Manual on Uniform Traffic Control Devices for Streets and Highways* will be brought in line with each other.

17. *Tire Coefficient of Friction.*—Experiments on striation of road surfaces to produce better local drainage give promise of increased coefficients of friction on wet roads. These experiments should be pursued and evaluated for their effect on determination of stopping sight distance. Similar experiments on road surface treatment should be initiated to see if diffuse reflection from wet roads can be improved for increased night vision.

Some thought has been given to types of analytical and empirical investigations that might be conducted to find solutions for the problem areas that have been listed. Some preliminary ideas are suggested in Chapter Two; but it would be premature to offer firm recommendations on methods of investigation at this time. Such recommendations should be made only after a review in depth of any current research that might be applicable, capabilities of research facilities, and alternative methods for conducting the investigations.

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APPENDIX A

ROAD CURVATURE EFFECTS ON HEADLIGHT SIGHT DISTANCE

An expression is derived for computing the minimum radius of curvature that will satisfy specific sight distance illumination requirements for a given headlamp beam pattern. Also a graphic method is shown for determining sight distance for any radius of curvature of the roadway for the given headlamp beam pattern.

Suppose it is desired to determine what minimum horizontal radius of curvature of roadway will comply with a headlamp sight distance which is limited by a required illumination intensity. Let the required intensity be denoted as I and the headlamp sight distance be D_I. Then, if photometric readings are taken at some distance, d, from the source of illumination (see Fig. A-1) there will be some offset, x, so that:

$$I_x = I\left(\frac{D_I}{d}\right)^2 \qquad \text{(A-1)}$$

in which I_x is the intensity at the offset, x.

This expression is valid if $\tan^{-1} x/d$ is small. Otherwise, the solution for the offset, x, is implicitly expressed as:

$$I_x = I\frac{D_I^2}{d^2 + x^2} \qquad \text{(A-2)}$$

From Figure A-2 it can be seen that:

$$\sin \alpha = \frac{x}{(d^2 + x^2)^{\frac{1}{2}}} = \frac{D_I}{2R} \qquad \text{(A-3)}$$

Then, the minimum radius of curvature, R, is computed from:

$$R = \frac{D_I \sqrt{d^2 + x^2}}{2x} \qquad \text{(A-4)}$$

If a headlamp beam pattern is specified as shown in the SAE *Journal* (1966, p. 710), for sealed beam headlamps, the horizontal and vertical profiles for a given illumination intensity can be drawn.

As in the case of any spherical radiation from a point source, illumination intensity is inversely proportional to the square of the distance from the source. Thus, the values given in Table I of the SAE *Journal* for the upper beam are used to compute profiles for an intensity of, say, 0.1 ft-candle. For instance, the illumination measured for the two points 3° above the beam axis and 3° to either side, is 500 candlepower. Then the distance to the 0.1 ft-candle isoline is $D_{0.1} = (500/0.1)^{\frac{1}{2}} = 70.7$ ft.

In Figure A-3, a plan view of the beam pattern for one headlamp is shown for the 0.1 ft-candle intensity range, for the plane ½° below the horizontal. If it is assumed that 0.1 ft-candle is required for sight distance, then the isoline must be drawn for that intensity for the combined beam pattern of the two headlamps. Although this is not too great a task, it would seem that the empirical method discussed by Moyer and Berry (*3*, Figs. 11 and 12) might be more suitable for design purposes.

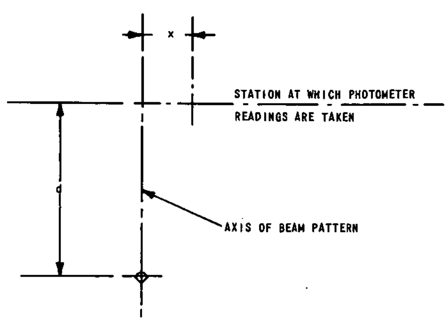

Figure A-1. Schematic diagram for measuring beam pattern.

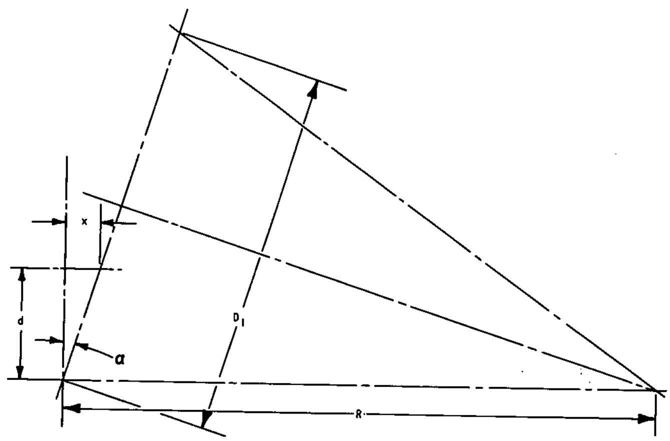

Figure A-2. Graphical solution for radius of curvature.

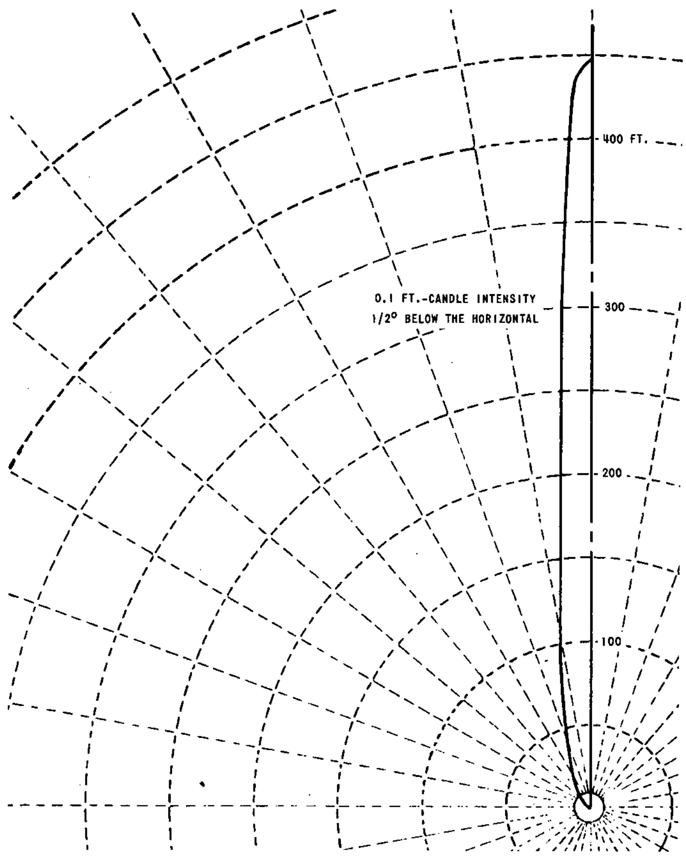

Figure A-3. Beam pattern of sealed-beam headlamp.

APPENDIX B

EFFECT OF SAMPLE SIZE AND MEASURING RESOLUTION ON THE ACCURACY OF AN AVERAGE VALUE

This appendix treats the question of how many measurements must be made (and with what measuring resolution) in order to achieve a level of confidence with which the average value of the sample will be within given accuracy limits. The topic has been introduced in this report to underscore the need for ascertaining that both instrumentation and measuring methods are compatible with the accuracy required, in determining vehicle, driver, and highway characteristics.

Procedures involving quantitative description of observed events always involve an information-gathering mechanism which translates characteristics of those events to numerical form. Naturally, some characteristics of the resultant information are influenced by the operation of this device. Specifically, the accuracy of the device will determine the accuracy of the data it yields.

Furthermore, if these data are collected for purposes of statistical inference, the accuracy of these inferences will be a function of the number of observations as well. In particular, as the number of observations increases the sample mean will approach the true mean with increasing probability. Thus, there will be an increased level of confidence associated with statements of the type, "the difference between the sample mean and the true mean is less than some specified value." This gives rise to the question, "How many measurements must be made, and with what precision, in order to estimate the true mean with acceptable accuracy at a given level of confidence?"

To aid the discussion the following example will be used. Suppose a sample of vehicles is being observed in order to estimate the mean speed of the population from which the sample was drawn. Suppose, further, that the data are collected by means of a radar device which registers vehicle speed in discrete intervals. If, for example, each of these measurement intervals has a width of 2 mph, then vehicles having actual speeds of, say, 49, 50.2, 51, 51.7, 52.5, and 52.8 mph would be recorded as 49, 51, 51, 51, 53, and 53, respectively, assuming interval cutoffs at 48, 50, 52, and 54 mph. Next, it is necessary to be confident that if a speed is registered as 51 mph the actual speed is somewhere between 50 and 52 mph.

For this purpose the assumption is made that the probability of an error—that is, of registering a speed in the wrong interval—is zero. This assumption need not be unrealistic, because a measuring device can be selected which has sufficient accuracy and a measurement interval of sufficient width that the likelihood of an error is negligible.

The first problem to be examined relates to the information gained when several speeds within the same interval are observed. Using the example, suppose a number, n, of speeds are observed, each giving a reading of 53 mph, and true mean speed of those n vehicles is to be estimated. Here the assumption is made that the speed of any one vehicle, if recorded exactly, would have an equal probability of being anywhere between 52 and 54 mph. This assumption will closely approximate actual observations whenever the width of the measurement interval is not too large.* Under this condition, the best estimate of the true mean speed is given by the midpoint of the interval; in the example, 53 mph.

Now the accuracy question may be formulated as follows. Assume that the desired statistically determined accuracy is a speed range of length r such that its midpoint, α, is also the midpoint of the measurement interval, which has width w. The probability that the mean, $\bar{x}$, of the true speeds lies in r may be written:

$$P_n = P(\alpha - r/2 < \bar{x} < \alpha + r/2) \qquad \text{(B-1)}$$

where n is the number of speeds observed. The effect of measurement accuracy (reduction of the interval, w) can be noted by writing Eq. B-1 in the form:

$$P_n(\rho) = P(½ - \rho/2 < Y < ½ + \rho/2) \qquad \text{(B-2)}$$

in which

$$Y = \frac{(x - \rho + w/2)}{w} \quad \text{and} \quad \rho = r/w$$

Clearly, as r increases relative to w, ρ increases and, therefore, P_n increases. In other words, as the measurement interval increases in size, the probability that $\bar{x}$ achieves the desired accuracy is diminished.

In order to evaluate $P_n(\rho)$ the distribution of $\bar{x}$ must be known. It has already been indicated that each speed, exactly measured, has a uniform distribution on the range $\alpha - w/2$ to $\alpha + w/2$. From this, the distribution of the mean of any number of speeds may be found. Using the results of Cramer (*28*), the distribution of the mean of observations is given by:

* Because too large an interval violates the assumption of a uniform distribution, and too small an interval may increase the probability of a speed registering in the wrong interval, care must be taken in choosing the interval width.

$$g_n(y) = \frac{n}{(n-1)!}\sum_{m=0}^{(ny)}(-1)^m\binom{n}{m}(ny - m)^{n-1}, \quad 0 \leq y \leq 1 \qquad \text{(B-3)}$$

where (z) is taken to mean the smallest integer less than z. This distribution has a mean value of α and a standard deviation equal to $1/\sqrt{12n}$.

Because tables of $g_n(y)$ are not readily available, it is convenient to know that this distribution approaches the normal curve very quickly. This is shown in Figure B-1 which displays $g_n(y)$ for $n = 1, 2, 3$, and the normal distribution, each of which has been standardized so as to have equal means and equal standard deviations. (It should be noted that this standardization allows direct comparison of shape, but precautions must be taken in comparing probabilities.) It is clear that the rapidity with which $g_n(y)$ approaches the normal is such that the normal distribution yields a rather good approximation with a sample as small as three observations.

Thus, depending on the needs of the experimenter, when n is large enough, $P_n(\rho)$ may be evaluated on the basis of the normal distribution having the same mean and standard deviation as $g_n(y)$. Otherwise, $g_n(y)$ must be used directly. In the former case tables are available; in the latter the equation is:

$$P_n(\rho) = 1 - \frac{2}{n!}\sum_{m=0}^{a}(-1)^m\binom{n}{m}(a - m)^n \qquad \text{(B-4)}$$

where $a = \frac{n}{2}(1 - \rho)$, and $0 \leq \rho \leq 1$. Because, in either case the standard deviation (σ) is $\frac{1}{\sqrt{12n}}$, which varies inversely

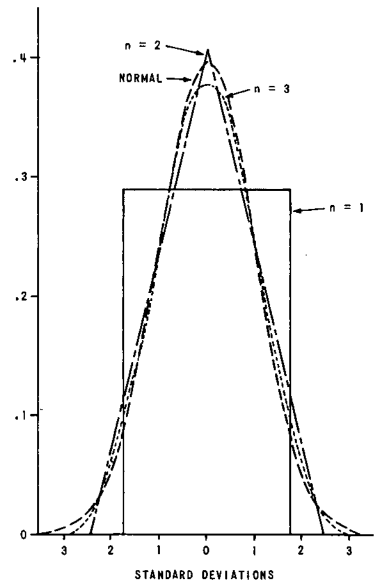

Figure B-1. A comparison of the normal distribution and distributions of means drawn from a uniform distribution.

as $\sqrt{n}$, the larger the sample size, the higher the probability that $\bar{x}$ will be near the true mean, and, therefore the larger $P_n(\rho)$ will be. This is demonstrated in Table B-1, where for any given confidence interval, indexed by ρ, the probability that the true sample mean is within that interval increases to the right, that is, as the sample size increases. Notice that the first entry in a cell is based upon sampling from a rectangular distribution, whereas the right-hand number derives from the normal approximation. Thus, to obtain an accuracy range equal to 0.4 times the measurement interval and a level of confidence of 0.75, three observations would be sufficient. If the level of confidence were to be 0.90, five observations would be required. In the speed example, this accuracy range would correspond, for instance, to 52.6 to 53.4 mph. If the desired accuracy range were smaller, more observations would be required, as implied by the table.

Here, again, it is of interest to note how well the probabilities based on the normal distribution approximate those derived from the uniform distributions, even when the sample size is very small.

The second problem to be discussed involves the collection of observations which are spread out over more than one measurement interval. The measurement of vehicle speeds again provides an example. The assumption that a speed registering in an interval implies the true speed was in that interval is still made. This problem is identical to that encountered whenever computations are based upon histograms, data tabulated by frequency, or data subject to rounding errors.

With this type of data the best estimate of the mean of the true distribution is given by the mean of the measured observations. That is:

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{m} f_i x_i \qquad \text{(B-5)}$$

where N is the sample size, x_i is the midpoint of the ith measurement interval, f_i is the number of measurements in that interval, and there is a total of m adjacent intervals.

In estimating the variance the usual estimator,

$$\frac{1}{N}\sum f_i x_i^2 - \bar{x}^2$$

will be biased. This is because in most intervals there are likely to be more true values on the side of the interval closer to $\bar{x}$; thus, the squared deviation between $\bar{x}$ and the midpoint of an interval is likely to be greater than the average squared deviations between $\bar{x}$ and the true values within the interval. According to Cramer (*28*) the appropriate correction, known as Shepard's correction, is equal to $w^2/12$, where w is the width of the measurement interval. Thus, the estimate of the standard deviation is:

$$\text{S.D.} = \left(\frac{1}{N}\sum f_i x_i^2 - \bar{x}^2 - \frac{w^2}{12}\right)^{\frac{1}{2}} \qquad \text{(B-6)}$$

This correction is approximate in that it depends upon the underlying distribution of the observations, but when that distribution is normal it is quite accurate.

The correction is necessary when w is large relative to the spread of the distribution. This condition corresponds directly to the use of a small number of measurement intervals. To illustrate, consider an experiment in which an infinite number of observations are randomly drawn from a normal distribution having a standard deviation of 1, and suppose these observations are grouped into intervals of width w. Clearly, the closer an estimate of the standard deviation is to 1, the better the estimate. If $w = ½$, then the resulting uncorrected $S.D. = 1.012$, whereas the corrected $S.D. = 1.001$. Thus, an improvement has resulted, although on a percentage basis it is quite small. If $w = 1$, the uncorrected $S.D.$ would be 1.040 and the corrected value would be 0.999, a 4% improvement. Finally if $w = 2$, an uncorrected value of 1.159 would result, and the corrected value would be 1.005, yielding a 15% improvement.

In computing confidence intervals for $\bar{x}$, its standard deviation (that is, the standard error of the mean) is utilized. This value is given as:

$$\text{S.E.} = \text{S.D.}/\sqrt{N} = \left(\frac{1}{N^2}\sum f_i x_i^2 - \frac{1}{N}\bar{x}^2 - \frac{w^2}{12N}\right)^{\frac{1}{2}} \qquad \text{(B-7)}$$

Here, it is seen, as before, that as N increases, $S.E.$ decreases, and the probability of $\bar{x}$ being near the true mean increases; that is, the level of confidence for any interval containing the true mean increases. This is demonstrated for intervals symmetric about the mean in the right-hand figures in the columns of Table B-1.

TABLE B-1

CONFIDENCE LEVEL [a] AS A FUNCTION OF SAMPLE SIZE

ρ	$n=1$		$n=2$		$n=3$		$n=4$		$n=5$		$n=10$	$n=100$	$n=200$
.1	.10	.14	.19	.19	.22	.24	.26	.27	.29	.30	.42	.92	.98
.2	.20	.27	.36	.38	.43	.45	.50	.51	.55	.56	.73	1.00	1.00
.4	.40	.51	.64	.67	.76	.77	.83	.83	.88	.88	.97	1.00	1.00
.6	.60	.70	.84	.86	.93	.93	.97	.96	.98	.98	1.00	1.00	1.00
.8	.80	.83	.96	.95	.99	.98	1.00	.99	1.00	1.00	1.00	1.00	1.00

[a] $P_n(\rho) = P\{a - \rho/2 < \bar{X} < a + \rho/2\}$
Lefthand value for $\bar{X}$ with density $gn(x)$
Righthand value for $\bar{X}$ normal

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