NCHRP

REPORT 600B

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Human Factors Guidelines for Road Systems

Collection B: Chapters 6, 22 (Tutorial 3), 23 (Updated)

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Collection B: Chapters 6, 22 (Tutorial 3), 23 (Updated)

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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 and Transportation 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 Federal Highway Administration, United States Department of Transportation.

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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.

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FOREWORD

By Charles W. Niessner
Staff Officer
Transportation Research Board

This report contains guidelines that provide human factors principles and findings for consideration by highway designers and traffic engineers. The guidelines allow the non-expert in human factors to more effectively consider the roadway user's capabilities and limitations in the design and operation of highway facilities.

The TRB, AASHTO, and the FHWA have been working since 2001 on two projects that together will help to promote greater safety for all road users. These two projects are the *Highway Safety Manual* (HSM) and the *Human Factors Guidelines for Road Systems* (HFG). These projects have been supported by funding from NCHRP and the FHWA. The TRB supports the *Highway Safety Manual* through the HSM Task Force and the *Human Factors Guidelines for Road Systems* through the Joint Subcommittee for the Development of a Human Factors Guideline for Road Systems.

The HSM and HFG promote improved safety for highway users and complement each other. They should be used together. Neither document is a substitute for national or state standards such as AASHTO's *A Policy on Geometric Design of Highways and Streets* or the *Manual on Uniform Traffic Control Devices*.

The HSM provides highway engineers with a synthesis of validated highway research and proven procedures for integrating safety into both new and improvement projects. It also provides practitioners with enhanced analytic tools for predicting and measuring the success of implemented safety countermeasures.

After using the HSM to develop possible design alternatives to improve safety on an in-service or planned intersection or section of roadway, the practitioner may then use the HFG to enhance the possible solutions. Successful highway safety depends on the consideration and integration of three fundamental components—the roadway, the vehicle, and the roadway user. Unfortunately, the information needs, limitations, and capabilities of roadway users are lacking in many traditional resources used by practitioners. The easy-to-use guidelines in the HFG provide the highway designer and traffic engineer with objective, defensible human factors principles and information that can be used to support and justify design decisions. The HFG will allow the non-expert in human factors to recognize the needs and limitations of the road user in a more effective manner and design roads that are safer for all.

When reviewing either existing or planned roads or intersections, highway designers and traffic engineers are strongly encouraged to use both the HFG and the HSM to identify and develop the safest solutions for road users.

NOTES ON PUBLICATION OF *HUMAN FACTORS GUIDELINES FOR ROAD SYSTEMS*

Chapter 6, Tutorial 3 of Chapter 22, and an updated Chapter 23 are contained herein. Chapters 1 through 5, 10, 11, 13, 22 (Tutorials 1 and 2), 23, and 26 were published previously as Collection A. Additional chapters will be developed under NCHRP Project 17-41 according to the priorities established by the project panel and are expected in late 2010. One additional project will most likely be needed to complete the guidelines. The problem statement for this final contract will be submitted to the AASHTO Standing Committee on Research for consideration at its March 2009 meeting.

Chapter 3 (Finding Information Like a Road User) and Chapter 4 (Integrating Road User, Highway Design, and Traffic Engineering Needs) are authored by Samuel Tignor, Thomas Hicks, and Joseph Mondillo.

Chapter 5 (Sight Distance Guidelines) and Tutorials 1 and 2 in Chapter 22 (Tutorials) present a revision of materials originally published as: Lerner, N., Llaneras, R., Smiley, A., and Hanscom, F. (2004). *NCHRP Web-Only Document 70: Comprehensive Human Factors Guidelines for Road Systems.* Washington, DC: Transportation Research Board.

Chapter locations and publication dates.

Chapter	Published in Report	Publication Date
1. Why Have Human Factors Guidelines for Road Systems?	600A	March 2008
2. How to Use this Document	600A	March 2008
3. Finding Information Like a Road User	600A	March 2008
4. Integrating Road User, Highway Design, and Traffic Engineering Needs	600A	March 2008
5. Sight Distance Guidelines	600A	March 2008
6. Curves (Horizontal Alignment)	600B	December 2008
7. Grades (Vertical Alignment)		Forthcoming
8. Tangent Sections and Roadside (Cross Section)		Forthcoming
9. Transition Zones Between Varying Road Designs		Forthcoming
10. Non-Signalized Intersections	600A	March 2008
11. Signalized Intersections	600A	March 2008
12. Interchanges		Forthcoming
13. Construction and Work Zones	600A	March 2008
14. Rail-Highway Grade Crossings		Forthcoming
15. Special Considerations for Urban Environments		Forthcoming
16. Special Considerations for Rural Environments		Forthcoming
17. Speed Perception, Speed Choice, and Speed Control		Forthcoming
18. Signing		Forthcoming
19. Variable Message Signs		Forthcoming
20. Markings		Forthcoming
21. Lighting		Forthcoming
22. Tutorials	600A,B	March, December 2008
23. References	600B	December 2008
24. Glossary		Forthcoming
25. Index		Forthcoming
26. Abbreviations	600A	March 2008
27. Equations		Forthcoming

All published chapters are available as individual PDF files and as a consolidated PDF file on the TRB website

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PART I Introduction

PART II Bringing Road User Capabilities into Highway Design and Traffic Engineering Practice

* See "Notes on Publication of *Human Factors Guidelines for Road Systems*" on facing page.

PART III Human Factors Guidance for Roadway Location Elements

CHAPTER 6

Curves (Horizontal Alignment)

TASK ANALYSIS ON CURVE DRIVING

Introduction

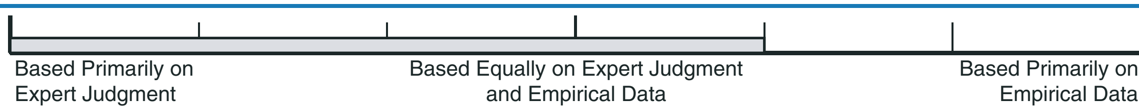
This guideline identifies the basic activities that drivers would typically perform while trying to safely navigate a single horizontal curve. This information is useful because (1) it can help identify segments of the curve driving task that are more demanding and require the driver to pay closer attention to basic vehicle control and visual information acquisition, and (2) it identifies the key information and vehicle control requirements in different parts of the curve driving task. This information has design implications because workload is influenced by design aspects such as design consistency, degree of curvature, and lane width. In particular, identifying high workload components of the curve driving task provides an indication of where drivers could benefit from having their driving tasks made easier to perform (e.g., clearer roadway delineation, wider lanes, longer radius), or benefit from the elimination of potential visual distractions.

Design Guidelines

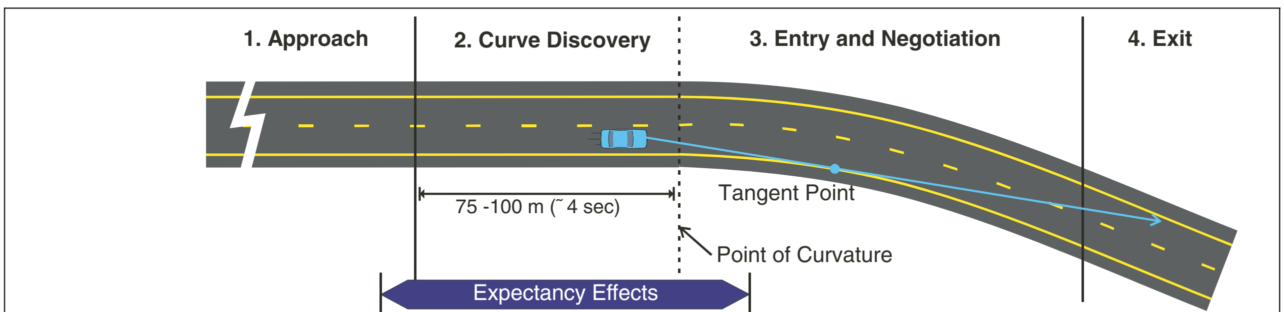
Because drivers have higher visual demands during curve entry and navigation—especially with sharp curves—curves should be designed to minimize additional workload imposed on drivers. Driver visual demands are greatest just before and during curve entry and navigation because drivers typically spend most of their time looking at the immediate roadway for vehicle guidance information.

Some General Implications for the Design of Horizontal Curves

- Avoid presenting visually complex information (e.g., that requires reading and/or interpretation) within 75 to 100 m or 4 to 5 s of the point of curvature, or within it.
- Key navigation and guidance information, such as lane markings and delineators/reflectors, should be clearly visible in peripheral vision, especially under nighttime conditions.
- Minimize the presence of nearby visual stimuli that are potentially distracting (e.g., signage/advertisements that "pop out" or irregular/unusual roadside scenery/foliage).
- Visual demands appear to be linearly related to curve radius and unrelated to deflection angle. Curves with a curvature of 9 degrees or greater are highly demanding relative to more gradual curves.



The figure and table below show the different curve segments, as well as key driving tasks and constraints.



	1. Approach	2. Curve Discovery	3. Entry and Negotiation	4. Exit
Key Driving Tasks	1.1 Locate bend 1.2 Get available speed information from signage 1.3 Make initial speed adjustments	2.1 Determine curvature 2.2 Assess roadway conditions 2.3 Make additional speed adjustments 2.4 Adjust path for curve entry	3.1 Adjust speed based on curvature/lateral acceleration 3.2 Maintain proper trajectory 3.3 Maintain safe lane position	4.1 Accelerate to appropriate speed 4.2 Adjust lane position
Visual Demands & Info Sources	**Low/Flexible** • Primarily environment driven	**Med. Increasing to High** • Curvature perception cues • Observing roadway conditions	**High** • Most fixations to tangent point	**Low** • Vehicle position information
Effective Info Modes	• Advisory/message signs	• Non-verbal (e.g., chevrons) and direct info (e.g., delineators)	• Direct info only (lane markings; raised markers)	• No constraints
Vehicle-Control Demands	• None	• Anticipatory positioning • Curve cutting	• Continuous heading adjustments	• Lane position adjustments
Primary Speed Influences	• Previous roadway elements & signage	• Expectations & curvature cues	• Expectations & lateral acceleration	• Posted speed or expectations

Discussion

The information about driving tasks in the previous page is taken from the task analysis described in Tutorial 3 that breaks down curve driving into its perceptual, cognitive, and psychomotor components. A key concept for understanding the curve driving task is the visual and vehicle-control demand, which refers to the amount of time that drivers are required to focus their attention on curve driving activities, such as acquisition of visual information and maintaining vehicle control, to the exclusion of other activities they could otherwise be doing while driving (e.g., scanning for hazards, viewing scenery, changing the radio station, etc.).

Visual demands: During the Approach segment, the time and effort that drivers typically spend acquiring information needed to safely navigate a curve is low and driven primarily by the driving environment (e.g., other vehicles, scenery). During Curve Discovery, visual demands increase to high levels at the point of curvature, as drivers scan the curve for information that they need to judge the degree of curvature. Visual demands are highest just after the point of curvature (Entry and Negotiation segment) and drivers spend most of their time looking at the tangent point to keep their vehicle aligned with the roadway (*1*, *2*, *3*). For more gradual curves (e.g., 3 degrees), drivers spend more time looking toward the forward horizon than the tangent point (*3*).

Vehicle-control demands: The driver workload imposed by the need to keep the vehicle safely within the lane is minimal up through the end of the Curve Discovery segment, at which point many drivers will adjust their lane position to facilitate curve cutting. Demands are highest during the Entry and Negotiation segment as drivers must continuously adjust the vehicle trajectory to stay within the lane. Moreover, these demands are higher for curves with a shorter radii and smaller lane width (*1*). During the Exit segment, drivers may adjust their lane position with minimal time pressure, unless there is another curve ahead.

Effective information modes: The type of curve-related sign/delineator information that is most likely to be useful to drivers differs in each curve segment. During the Approach, drivers have fewer visual demands and have more time available to read more complex signs, such as speed advisory signs. During the Curve Discovery segment, conspicuous non-verbal information, such as chevrons, are more effective because drivers spend more time examining the curve and have less time available to read, comprehend, and act on text-based information. During Entry and Negotiation, drivers spend most of their time looking at the tangent point, and only direct information presented where they are looking (e.g., lane markings) or information that can be seen using peripheral vision (e.g., raised reflective marking at night) should be relied upon to communicate curve information.

Speed selection: Driver expectancy and speed-advisory sign information form the primary basis for speed selection; however, the effectiveness of advisory information may be undermined by expectancy and roadway cues (*4*). Curve perception also plays an important role in speed selection and inappropriate curvature judgments (e.g., in horizontal curves with vertical sag). Once drivers are in the curve, lateral acceleration felt by drivers and likely vehicle handling workload provide the primary cues for adjusting speed.

Expectancy effects: Driver expectations about a curve and, more broadly, design consistency are important factors in drivers' judgments about curvature and corresponding speed selection during the Curve Discovery segment (*1*). While direct cues, such as lane width and the visual image of the curve, influence speed selection, expectations based on previous experience with the curve and roadway (e.g., previous tangent length) also significantly influence speed selection (*4*). Mitigations to recalibrate driver expectancies (e.g., via signage) would likely be most effective prior to the Curve Discovery segment.

Design Issues

Visual demands appear to be related linearly and inversely to curve radius, but not to deflection angle. Curves sharper than 9 degrees are significantly more demanding than shallower curves or tangents, however, there is no clear, unambiguous threshold regarding what constitutes a sharp curve based on workload data (*1*, *2*). Also, curve direction does not seem to affect workload (*2*).

Additionally, it is unclear whether the 75 to 100 m length of the Curve Discovery segment is based on distance or time. The primary studies that investigated visual demand used the same fixed 45 mi/h travel speed, so it is currently unknown whether the 75 to 100 m fore-distance applies with other speeds (*1*, *2*).

Cross References

The Influence of Perceptual Factors on Curve Driving, 6-4
Speed Selection on Horizontal Curves, 6-6
Countermeasures for Improving Steering and Vehicle Control Through Curves, 6-8
Countermeasures to Improve Pavement Delineation, 6-10
Signs on Horizontal Curves, 6-12

Key References

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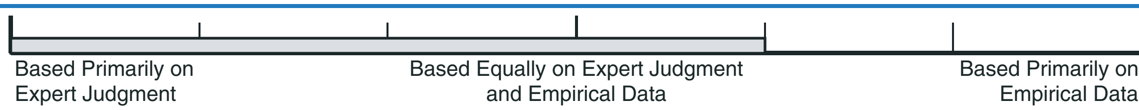
THE INFLUENCE OF PERCEPTUAL FACTORS ON CURVE DRIVING

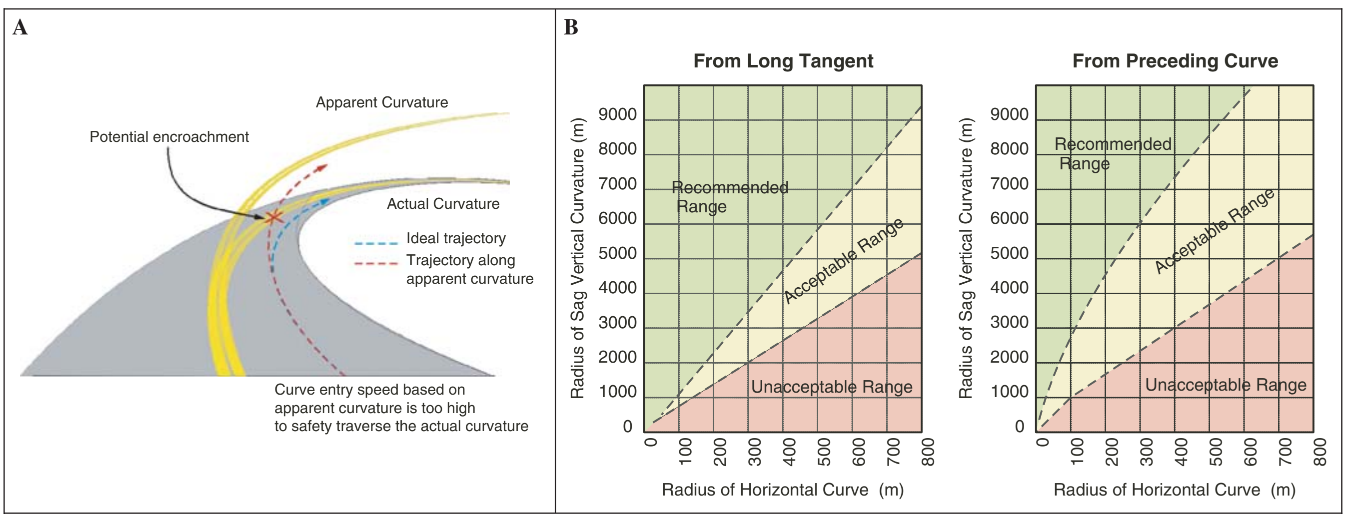
Introduction

The perceptual factors in curve driving refer to the driver's use of visual information to assess the curvature of an upcoming curve. This activity is important because a driver's perception of an upcoming curve's radius forms the primary basis for making speed and path adjustments prior to curve entry. The curve radius as seen from the driver's perspective is called the *apparent radius*. Although drivers will use speed information from signs, in practice, driver speed selection in curves is heavily influenced by roadway features (*1*), and the apparent radius appears be the primary determining factor of speed at curve entry (*2*). The primary design challenge regarding curve perception is that the apparent radius can appear distorted—either flatter or sharper—depending on the topography and other road elements. Of particular concern are combination curves that include a vertical sag superimposed on a horizontal curve. From the driver's perspective, this combination makes the horizontal curve appear flatter than it actually is (See A in the figure below). Consequently, drivers may be inclined to adopt a curve entry speed that is faster than appropriate based on horizontal curvature alone.

Design Guidelines

Sag horizontal curves that have a visual appearance (apparent horizontal radius) that is substantially different from the plan radius should be given careful consideration because they may lead to curve entry speeds that are faster than expected based on horizontal curvature alone.





A. A vertical sag curve produces a visual image (shaded roadway) that a driver would perceive as having an apparent radius that is larger than the actual radius.

B. Nomographs indicating vertical and horizontal curve radius combinations that result in apparent radii that may result in curve entry speeds that are unintentionally faster than expected based on horizontal curvature alone (red shaded region), and which possibly represent a safety risk (*2*).

Note that the nomographs present vertical curvature in terms of radius (in meters) and not *K*, which is the typical approach for representing vertical curvature. The reason for presenting curvature as a radius is that the geometric calculations for computing visual distortion rely on circular arcs. The nomographs can be used to provide a "rule of thumb" check for potentially problematic curve combinations assuming the vertical curvature component can be generally approximated by a circle with an arc intersecting the low point of Type III curves and vertical points of curvature on both sides.

Discussion

Curve perception is an important part of curve driving because, in the absence of extensive experience with a curve, drivers must rely on their judgments about a curve to select a safe speed for curve entry. Speed signage information can assist drivers; however, evidence suggests that this information is not a primary source for speed selection in curves (*1*). Therefore, driver expectations (influenced by design consistency) and the visual information the driver obtains about the curve are the primary basis for speed selection.

Sag horizontal curves can cause drivers to significantly underestimate the sharpness of a curve because of a visual distortion from the driver's viewing perspective; i.e., the apparent radius appears to be longer than the plan radius. Thus, these sag horizontal curves, are also associated with higher entry speeds and crash rates (*2*, *3*).

The optical aspects of this phenomenon have been derived analytically, and the results were used to make the nomographs presented on the previous page. Horizontal and vertical curve radius combinations that fall in the unacceptable range are associated with significant visual distortion, and also associated with higher than 85th percentile speeds and higher crash rates (*2*). Note that this validation is based on European data, and these findings have not been investigated on US roads. However, the optical properties of this phenomenon are universal and should be equally applicable to all drivers (*4*). This analytical work also assumes a 75 m viewing distance, which is comparable to the start of the Curve Discovery segment of curve driving, in which drivers spend most of their time inspecting the curve. Distortion effects may be reduced somewhat at further viewing distances; however, assuming a 75 m viewing distance is consistent with driver behavior and is more conservative.

Visual distortion also occurs when crest vertical curves are superimposed on horizontal curves; such curves appear sharper than the plan radius. This typically results in slower 85th percentile entry speeds (*2*, *3*). However, a crest horizontal curve with a vertical curvature that approximates a circular radius of *less than 3 times* the horizontal curve radius could present a discontinuous visual image of the curve (e.g., the part of the roadway just behind the crest is occluded) (*2*). Such a crest horizontal curve is potentially inconsistent with driver expectations and could compromise roadway safety by causing drivers to suddenly brake hard if they are surprised by the curve appearance. However, there are currently no empirical data showing that this is an actual safety issue.

Design Issues

A summary of the relevant research findings regarding curve perception in general and the corresponding degree of empirical support is shown in the table below. While no specific values or recommendations can be made for these aspects, it is useful to take them into consideration during curve design, especially if other aspects of the curve design suggest that there may be a potential problem with driver perception of the curve radius.

Aspect	Effect	Empirical Support
Superimposed Vertical Sag	Makes a curve appear flatter	Strong
Cross Slope	For sag horizontal curves, the greater the cross slope and lane width, the greater the apparent flattening of the horizontal curve	Analytical evidence
Superimposed Vertical Crest	Makes a curve appear sharper and may cause discontinuities in curve	Strong
Deflection Angle	Holding radius constant, greater deflection angle makes the curve appear sharper, especially for smaller radii	Moderate
Delineators	Delineators provide drivers with more information to judge the curve radius, which improves accuracy of these judgments	Moderate
Spiral	May make curve appear flatter, or make curve perception more difficult, because the onset of the curve is less apparent	Indirect
Signage	Drivers perceive curve as "riskier" if signs indicate that the curve is hazardous	Suggestive

Cross References

Task Analysis of Curve Driving, 6-2

Key References

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SPEED SELECTION ON HORIZONTAL CURVES

Introduction

Various sources attempt to examine speed data for roadway geometry and to determine desirable speeds for horizontal curves. AASHTO policy defines design speed as “a selected speed used to determine the various geometric design features of the roadway” (*1*).

The design speeds on horizontal curves should be set at a value determined by AASHTO policy and factors determined from a survey of state DOTs. AASHTO policy (*1*) considers factors such as functional classification, rural vs. urban environment, and terrain type; state DOTs typically consider factors such as functional classification, legal speed limit (as well as legal speed limit plus an adjustment value of 5 or 10 mi/h), anticipated volume, terrain type, development, costs, and design consistency.

Design Guidelines

A number of vehicle, driver, and roadway variables should be considered when determining speed limits for horizontal curves. A procedure to calculate appropriate speeds has been adapted from Charlton and de Pont (*2*) and is outlined below. If these factors are common at an intersection location, then consideration should be given to modifying the gap acceptance design assumptions.

Step	Procedures for Determining Curve Advisory Speed Limits
1	Determine curve radius (*R*), superelevation, and offset distance from center of lane to any visual obstruction (*O*).
2	Determine the vehicle’s maximum possible lateral acceleration and braking coefficient. The maximum lateral acceleration is limited by rollover stability for most heavy vehicles and by tire adhesion for passenger cars. Typical values to use for dry conditions are 0.35 *g* for laden heavy vehicles, 0.7 *g* for buses and SUVs, and 0.8 *g* for passenger cars. The braking coefficient reflects the maximum braking efficiency that can be achieved and should be 0.9–1.0 for passenger cars and 0.5– 0.6 for heavy vehicles. Assume a reaction time (T_r) of 2 s.
3	Calculate the maximum possible speed (in km/h) limited by lateral acceleration using the formula: $$V = \sqrt{127R\,(lateral\_acc + superelevation)}$$
4	4.1 From this speed, calculate the safety factor (SF) using the equation: $SF = 1 + 0.03476\,V - 0.00004762\,V^2$ 4.2 Divide the maximum lateral acceleration value by the safety factor (*SF*), and recalculate the speed using the equation in step 3. This is the desirable maximum speed limited by lateral acceleration, V_{acc}. $$V_{acc} = \sqrt{127R\left(\frac{lateral\_acc}{SF} + superelevation\right)}$$
5	5.1 Calculate the sight distance using the equation: $$SD_{acc} = 2R\cos^{-1}\left(\frac{R-O}{R}\right)$$ 5.2 Based on a safety factor of 2, set the braking coefficient (*d*) to half the maximum braking efficiency value. Then, set the stopping sight distance equal to the sight distance calculated above and solve for speed (V_{sight}) in the following stopping distance equation: $$SD_{stop} = SD_{acc} = \frac{T_r V_{sight}}{3.6} + \frac{V_{sight}^2}{254d} \quad \rightarrow \quad V_{sight} = 127\,d\left(-\frac{T_r}{3.6} + \sqrt{\left(\frac{T_r}{3.6}\right)^2 + \frac{4\,SD_{acc}}{254\,d}}\right)$$
6	The maximum desirable speed for the particular vehicle in the curve is the lesser of the two maximum speed values, V_{acc} and V_{sight}.

Variables

R = Curve Radius (m)
O = Offset Distance from center of the lane to the obstruction (m)
T_r = Driver Reaction time (seconds)
d = Breaking Coefficient
V = Vehicle Speed (km/h)
SD_{stop} = Stopping Sight Distance
SD_{acc} = Sight Distance
V_{acc} = Desirable maximum speed limited by lateral acceleration (km/h)
V_{sight} = Desirable maximum speed limited by sight distance (km/h)

Based Primarily on Expert Judgment | Based Equally on Expert Judgment and Empirical Data | Based Primarily on Empirical Data

Discussion

Drivers' failure to accurately judge the appropriate driving speed on horizontal curves can have safety consequences. The Fatality Analysis Reporting System (FARS) indicates that 42,815 people were killed in 38,309 fatal crashes on the US highway system in 2002. Approximately 25% of these crashes occurred along horizontal curves. These crashes occurred predominantly on two-lane rural highways that are often not part of the state DOT system. Approximately 76% of curve-related fatal crashes were single-vehicle crashes in which the vehicle left the roadway and struck a fixed object or overturned; conversely only 11% of curve-related crashes were head-on crashes.

Speed selection by drivers on horizontal curves reflects a variety of vehicle, driver, and roadway factors. For example, drivers of vehicles with larger engines, and greater acceleration capacity, approach curves differently than other drivers (*3*). Experienced and middle-aged drivers report less accurate estimates of perceived speed than do younger and less-experienced drivers along roadway curves (*4*). Visual misperceptions may occur when the horizontal curve is combined with a vertical curve. For example, on-road records of vehicle speed were demonstrated to be consistent with a misperception hypothesis on crest combinations (*5*); i.e., the horizontal radius is perceived to be shorter than it actually is. In a safety research study (*6*), relationships of safety to geometric design consistency measures were found to predict speed reduction by motorists on a horizontal curve relative to preceding curve or tangent, average radius, and rate of vertical curvature on a roadway section and ratio of an individual curve radius to the average radius for the roadway sections as a whole. A review of vehicle speed distributions and the variation of vehicle speed around single road curves found that the pattern of variation in vehicle speeds along a road curve was highly dependant on the level of curvature; this effect was more pronounced for curves of radius less than 250 m (*7*). While radius of curvature is not the only factor that influences selected speed on horizontal curves (*8*), it may be the most important factor (*9*).

Determining speeds for horizontal alignment is a complex mix of personal judgment, empirical analysis, and AASHTO/state DOT guidelines. A number of sources provide equations and procedures that reflect the complexity of speed selection on curves by drivers. A series of speed prediction equations for passenger vehicles on two-lane highways as a function of various characteristics of the horizontal curve is provided in Anderson, Bauer, Harwood, and Fitzpatrick (*6*). A series of steps that can be used to determine maximum desirable speed is provided in Charlton and de Pont (*2*).

Design Issues

Transportation Research Circular 414 (*10*) stated factors contributing to higher crash frequency on horizontal curves include higher traffic volumes, sharper curvature, greater central angle, lack of a transition curve, a narrower roadway, more hazardous roadway conditions, less stopping distance, steep grade on curve, long distance since last curve, lower pavement friction, and lack of proper signs and delineation.

Cross References

The Influence of Perceptual Factors on Curve Driving, 6-4

Key References

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COUNTERMEASURES FOR IMPROVING STEERING AND VEHICLE CONTROL THROUGH CURVES

Introduction

Successful navigation of curves depends on accurate steering and speed control in order to minimize lateral acceleration within the lane. Design of alignments that conform to driver expectations and typical behaviors will enhance the driver's ability to control the vehicle. This guideline provides strategies for implementing curve geometries that help drivers maintain proper lane position, speed, and lateral control through curves. Delineation treatments that improve vehicle control are presented in the "Countermeasures to Improve Pavement Delineation" guideline.

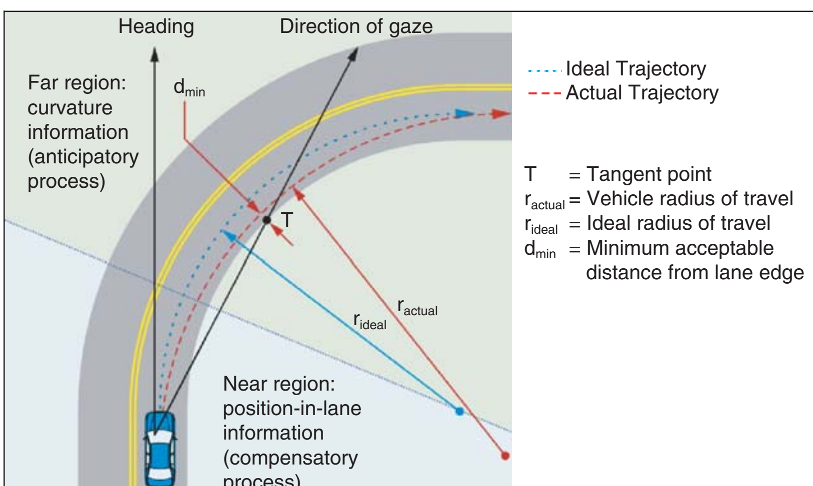
Design Guidelines

The following guidelines present strategies for designing geometric features that will enhance steering control.

Curvature	• Minimize the use of controlling curvature (i.e., maximum allowable curvature for a given design speed).
Spirals	• Spiral transition curves should be used whenever possible, particularly for curves on roads with high design speeds (e.g., 60 mi/h or greater). • Spiral curve lengths should equal the distance traveled during steering time (i.e., 2 to 5 s, which equates to roughly 60–140 m for two-lane highways and 80–140 m for freeways). • The recommended curve radius for two-lane highways with a speed limit of 50 mi/h is 120 to 230 m, with clothoid parameters between 0.33 and 0.5 R. Circular arc lengths should equate to at least a 5 s pass-through time.
Reverse Curves	• Do not use tangent sections in reverse curves when the distance between the exit of the first curve and the entrance of the second curve is short enough to encourage a curved path through the tangent (e.g., 80 m or less for two-lane highways and 135 m for freeways).
Superelevation	• Superelevation should be designed to result in zero lateral acceleration through the curve at design speed.
Design Consistency	• Avoid sharp, isolated curves and maintain consistency in the design of superelevation, road width, and other curve features to improve conformance with drivers' expectations.

Based Primarily on Expert Judgment | Based Equally on Expert Judgment and Empirical Data | Based Primarily on Empirical Data

The figure below illustrates the various concepts that describe how drivers navigate a curve: visual components related to guidance and lane-keeping, the path choice model, and the combination of processes that govern curve traversal.



- Driver enters curve to the left of the lane center
- Far region provides cues for predicting curvature and steering angle in closed-loop anticipatory control process.
- Near region (≤7 degrees down from horizon) provides cues for correcting deviations from path in open-loop compensatory control process.
- Driver follows trajectory with radius of curvature (r_{actual}) greater than radius at center of lane (r_{ideal}) and that brings the vehicle to a minimum distance (d_{min}) from the roadway edge line at its apex.
- Driver fixates on curve tangent point through the curve.

Adapted from Donges (*1*); Levison, Bittner, Robbins, and Campbell (*2*); and Spacek (*3*). Figure not to scale.

Discussion

The steering control task has been modeled as a two-level process composed of an open-loop anticipatory component (far view) for predicting curvature and steering angle, and a closed-loop compensatory component (near view) for correcting deviations from the desired path (*1*). However, this two-level model does not adequately describe some path-decision behaviors such as curve-cutting. Also, drivers often make anticipatory steering actions based on an internal estimate of the vehicle characteristics and on previously perceived curvature, rather than on direct visual feedback, while paying attention to other aspects of the driving task (*4*).

Geometric alignment and delineation features affect the driver's perception of curvature and therefore influence curve entry speed. Curve geometries that do not meet the driver's perceptual expectations may result in inappropriate entry speeds that require speed and steering corrections within the curve in order to avoid excessive lateral acceleration and a potential loss of control. Inaccuracies in anticipatory assessment prior to curve entry generally increase with curvature, and compensatory control actions to correct these errors are greatest in sharp curves (*4*, *5*).

In general, drivers tend to cut curves. In one study (*3*), almost one-third of drivers cut left-hand curves and 22% cut right-hand curves. Drivers compensate for inadequate steering adjustment at curve entry by following a trajectory with a radius that is larger than the ideal radius (i.e., radius at the center of the lane), with the vehicle traveling within some minimum distance of the edge line at its apex (*2*, *7*). Vehicle path radius at the point of highest lateral acceleration correlates with higher crash rates.

Design Issues

Curvature: Road curvature significantly affects average lateral position error. As curves become sharper, there is a corresponding increase in workload, which can result in an increase in edge line encroachments on the inside lane (*6*, *7*). Restrictive geometric characteristics (e.g., sharper curves, narrower shoulders, and steeper grades) are more likely to lead to centerline encroachments than those that are less constraining; however, high curvature has the greatest adverse effect on crash rates and driving performance in horizontal curves.

Spiral curves: Spirals that are designed to match drivers' natural steering behavior offer a gradual increase in centrifugal force and facilitate superelevation transitions, which can improve the vehicle's lateral stability (*6*, *7*, *8*). However, overly long spiral transitions can lead to misleading perception of the sharpness of curvature, inappropriate entry speed, and unexpected steering and speed corrections within the curve. The most desirable spiral length is equal to the distance traveled during the steering time (nominally 2 to 5 s depending on radius).

Reverse curves: Tangent sections of appropriate length can provide effective transitions between curves in a reverse curve alignment. However, if the tangent section is too short, drivers may follow a curved rather than straight trajectory through the tangent section (*7*). To match the alignment to drivers' typical steering behavior, the transitional tangent should be long enough to allow straightening of the vehicle through the transition (if possible); otherwise, the transitional tangent should not be used.

Design consistency: Drivers are more likely to make appropriate speed and steering decisions when the roadway design meets their perceptual expectations. Consistency in curve features, such as superelevation, lane width, curvature, etc., help reduce workload and therefore improve stability in steering control (*6*).

Cross References

The Influence of Perceptual Factors on Curve Driving, 6-4
Speed Selection on Horizontal Curves, 6-6
Countermeasures to Improve Pavement Delineation, 6-10

Key References

1. Donges, E. (1978). Two-level model of driver steering behavior. *Human Factors, 20*(6), 691-707.
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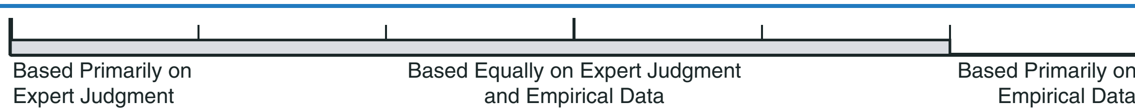
COUNTERMEASURES TO IMPROVE PAVEMENT DELINEATION

Introduction

This guideline describes countermeasures that support improvements in curve detection and driver performance through the use of pavement surface markings, such as edge lines, raised retroreflective pavement markers (RRPM), transverse stripes, etc. These markings provide primarily non-verbal cues that promote improved vehicle control through earlier detection and recognition of curves, reductions in speed, and adjustments to lateral position.

Design Guidelines	
General	• Use surface delineations that are characterized by small gaps, long dashes, and short repetition cycles. • Use combinations of treatments wherever practical to increase overall effectiveness.
Edge line/ Centerline	• Use edge lines when curves are sharp or frequent, on narrow roads, or in the vicinity of crossing roadways or major driveways. • Use the widest possible edge lines and centerlines to maximize visible surface area. • When possible, use striping materials with highly retroreflective characteristics to implement edge lines and centerlines.
RRPM	• Combine RRPM with edge lines/centerlines. • Use pairs of RRPM on the outside edges of the centerline for very sharp curves (≥ 12 degrees); for flatter curves, single RRPMs are sufficient. • Place RRPMs 244 m in advance of the curve. Space markers at 40 m intervals for sharp curves and 80 m intervals for flatter curves.
Transverse Stripes	• When practical, implement transverse stripes as graduated rumble strips. • Space stripes to achieve 0.5 s intervals at the desired deceleration rate (e.g., 0.9 m/s^2)
"SLOW" text with arrow	• Use "SLOW" with arrow surface markings in the tangent section approximately 70 m before the curve to augment treatments in high-hazard areas or at sharp curves.



The following table indicates various pavement marking treatments and their strengths for enhancing speed reduction, lane-keeping, and curve detection and recognition.

Treatment Type	Strengths
General – Surface markings	Strongest curvature cues and short-range steering control (compensatory control)
General – Post-mounted chevrons	Strongest guidance cues and long-range guidance (anticipatory control)
Treatment Combinations	Superior effectiveness compared with individual treatments
Edge line/Centerline	Strongest for curve recognition, curvature perception, and reduction of lateral variability. Discontinuities in edge line aid in recognizing upcoming intersections, driveways, etc.
RRPM	Improving visibility of edge lines and centerlines. Reducing lane encroachments. Both visual and rumble effects provide encroachments cues.
Transverse Stripes	Speed reduction. May be more effective at reducing higher (> 85^{th} percentile) speed driving than lower speed driving.
"SLOW" Text with Arrow	Speed reduction and curve ahead warning.

Discussion

Road delineations provide cues that assist drivers in detecting curves and assessing the level of curvature. Road surface markings provide the strongest curvature cues and are best for providing short-range steering control cues (compensatory control—see "Countermeasures for Improving Steering and Vehicle Control Through Curves"), while chevron designs on post-mounted panels give the strongest guidance cues and are best for long-range guidance (anticipatory control). Under conditions of reduced visibility, steering performance improves in the presence of road surface delineations that are characterized by small gaps, long dashes, and short repetition cycles.

Edge lines improve perception of curvature, curve recognition distance, and lane-position stability. Roads with edge lines exhibit fewer crashes than those without edge lines, particularly in combination with narrow widths, wet pavement, and/or high-hazard areas (*1*). Surface area has the greatest effect on edge line (and centerline) visibility—effectiveness increases with wider edge lines. Also, the effectiveness of these stripes increases with the level of retroreflectivity.

Raised reflective pavement markers are highly effective at improving curve visibility and reducing crashes, especially when used in combination with centerlines and edge lines (*2*). They can be particularly useful as a cue for warning of lane encroachment because the raised marker provides tactile as well as visual stimulus. As with edge lines, the effectiveness of RRPMs increases with retroreflectivity.

Transverse stripes refers to painted or taped stripes that are applied perpendicularly across the roadway alignment. Typically, these stripes are separated by decreasingly graduated spacings in order to encourage speed reduction by creating a sensation of increased speed when the vehicle is traveling at constant speed. The effectiveness of transverse stripes has been mixed; while some studies report reductions in speed at curve entry (*3*), others report either no reduction or a slight increase in speed (*4*). Transverse stripes are most effective when implemented as rumble strips because they provide both visual and tactile stimuli.

"Slow" text with arrow refers to the word "Slow" marked in elongated letters with an arrow above it pointing in the direction of the curve and transverse lines before and after the symbols. This treatment may be effective at speed reduction, especially in late night driving when drivers are more likely to be impaired by fatigue or alcohol (*5*).

Combinations of treatments are generally more effective than any single treatment, especially when the combination includes rumble strips. Curve recognition, lane position, and number of encroachments are improved when RRPMs are used in conjunction with edge line/centerline markings compared with single treatments.

Design Issues

In general, centerline treatments tend to cause drivers to shift lateral position away from the centerline, while edge line treatments result in a lateral shift toward the centerline. RRPMs may reduce nighttime corner cutting in left-hand curves but increase corner cutting in right-hand curves (*6*).

Several treatments, such as transverse stripes and widening of inside edge markings at the curve, may have a greater effect on driver performance for high-speed drivers (above 85th percentile speeds) than for lower-speed drivers. These treatments should be considered in hazard areas where speed is a prevalent factor in elevated crash rates (*3*).

Cross References

Speed Selection on Horizontal Curves, 6-6
Countermeasures for Improving Steering and Vehicle Control Through Curves, 6-8

Key References

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SIGNS ON HORIZONTAL CURVES

Introduction

Prior to a change in the horizontal alignment of a roadway, information about this change should be conveyed to drivers via roadway signs. This information should be communicated in a concise and efficient manner such that drivers have time to process the information and adjust their speed as well as alter the vehicle path appropriately. Notification of an upcoming curve is typically conveyed using curve warning signs, which indicate whether the curve is to the right or the left; they are sometimes accompanied by advisory speed signs. The use of dynamic warning signs to alert drivers of a curve and/or their vehicle speed has also gained acceptance as an effective means of communication.

Researchers disagree as to how advance warnings should be presented to drivers, i.e., through text or through symbols. But all agree that the key to effective warning is to notify the driver of the upcoming curve so that the driver can change the speed or path of the vehicle—or both. Individual studies on the effectiveness of advance warning signs vary considerably with respect to sign placements, sign messages, horizontal curve radii, and driver populations. Designers should consider such variables when making design decisions. Also, any information considered for use in curve signs should not be in conflict with current design standards in publications such as the MUTCD.

Design Guidelines

The tables below show the guidelines for advance placement of curve warning signs related to advisory/85th percentile speed, as well as spacing for chevrons—both are presented as a function of posted or advisory speeds (Adapted from McGee and Hanscom (*1*)).

Posted or 85th Percentile Speed (mi/h)	Advance Placement Distance (ft) for Advisory Speed of the Curve (mi/h) of						
	10	20	30	40	50	60	70
20	n/a[1]	–	–	–	–	–	–
25	n/a[1]	n/a[1]	–	–	–	–	–
30	n/a[1]	n/a[1]	–	–	–	–	–
35	n/a[1]	n/a[1]	n/a[1]	–	–	–	–
40	n/a[1]	n/a[1]	n/a[1]	–	–	–	–
45	125	n/a[1]	n/a[1]	n/a[1]	–	–	–
50	200	150	100	n/a[1]	–	–	–
55	275	225	175	100	n/a[1]	–	–
60	350	300	250	175	n/a[1]	–	–
65	425	400	350	275	175	n/a[1]	–
70	525	500	425	350	250	150	–
75	625	600	525	450	350	250	100

[1] No suggested distance is provided for these speeds, as the placement location depends on site conditions and other signing to provide an adequate advance warning for the driver.

Advisory Speed Limit (mi/h)	Chevron Spacing (ft)
15	40
20	80
25	80
30	80
35	120
40	120
45	160
50	160
55	160
60	200
65	200

NOTE: The above spacing distances apply to points within the curve. Approach and departure spacing distances are twice those shown above.

Discussion

Numerous studies have shown the effectiveness of advanced warning signs for curves (*2*, *3*, *4*, *5*). Typical improvements in driving performance are reductions in speed, fewer lane excursions, and generally fewer crashes—see also the table below. From a driver's perspective, the key advantage of advance warning signs is a notification that a (possibly) unexpected change in the horizontal alignment of the roadway is imminent. Signing can be used to notify the driver of an upcoming curve in many ways, including proper positioning along a driver's line of sight, fluorescent illumination, flashing beacons (*5*), or dynamic warnings. In this regard, designers are cautioned to avoid overloading the driver with extraneous information that might distract him or her from the primary task of maintaining safe control of the vehicle (*6*).

Improvement	Reference	Findings
Fluorescent Yellow Microprismatic Chevron Treatments	*2*	Weighted average decrease in speeds at the curve point of curvature of about 1 mi/h for both the mean and 85th percentile versus the existing standard yellow ASTM Type III signs. 38% overall reduction in edge line encroachments.
Fluorescent Yellow Chevron Posts	*2*	Speeds reduced slightly.
Fluorescent Yellow Microprismatic Curve Warning Signs	*2*	The overall number of vehicles initiating deceleration before reaching the curve warning sign was increased by 20%. However, the study found small and inconsistent effects on speeds approaching curves.
Standard Red Reflectorized Border on Speed Limit Sign	*2*	The red border had the greatest effect on speeds during the day for both passenger vehicles and heavy trucks. Daytime mean and 85th percentile speeds of heavy trucks were found to decrease by ≈ 4 mi/h.
Addition of Flags, Flashers on Existing Warning Signs	*3*	The changes made to roadway surface included more reflective centerlines (CLs), more reflective edge lines (ELs), wider ELs, the additional of raised retroreflective pavement markers, and the inclusion of horizontal signing warning of approaching curves.
Dynamic Advance Curve Warning System	*4*	Results found decreases in mean speeds from 2 to 3 mi/h.
Different Pavement Markings and Raised Retroreflective Pavement Markers	*5*	Nighttime average speed reductions for the warning sign with flashing lights (5.1%), the combination horizontal alignment/advisory speed sign (6.8%), and flashing lights on both warning signs (7.5%).

Design Issues

In a literature synthesis of the knowledge and practice, the physical and performance characteristics of heavy vehicles that interact with highway geometric design criteria and devices were examined (*7*). The synthesis notes that dynamic curve warning systems for trucks—especially highly accurate, sophisticated systems that incorporate vehicle parameters such as speed and weight—may help warn drivers of curves ahead and mitigate rollover crashes.

Cross References

Speed Selection on Horizontal Curves, 6-6

Key References

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CHAPTER 22

Tutorials

Tutorial 1: Real-World Driver Behavior Versus Design Models

Much of the information on sight distance presented in Chapter 5 reflects the application of empirically derived models to determine sight distance requirements. Such models, while valuable for estimating driver behavior across a broad range of drivers, conditions, and situations, have limitations.

This tutorial discusses how driver behavior as represented in sight distance models may differ from actual driver behavior. The design models presented in Chapter 5 use simplified concepts of how the driver thinks and acts. This simplification should not be viewed as a flaw or error in the sight distance equations. These models are a very effective way of bringing human factors data into design equations in a manner that makes them accessible and usable. After all, the intent of a sight distance equation is not to reflect the complexities of human behavior but to bring what we know about it into highway design in a concise, practical way. However, like any behavioral model, models for deriving sight distance requirements are not precise predictors of every case and there may be some limitations to their generality. Therefore, having an understanding of certain basic principles of human behavior in driving situations is useful to better interpret these models and to understand how they may differ from the range of real-world driving situations.

Sight distance formulas for various maneuvers (presented in Chapter 5) differ from one another, but they share a common simple behavioral model as part of the process. The model assumes that some time is required for drivers to perceive and react to a situation or condition requiring a particular driving maneuver (i.e., PRT), which is followed by some time (i.e., MT) and/or distance required to execute the maneuver. Sight distance equations for some maneuvers may contain additional elements or assumptions; however, all have this basic two-stage model somewhere at their core.

The two equations that follow show two versions of the general, two-component model. In both versions, the first term shows the distance traveled during the PRT component and the second term shows the distance traveled during the MT component. The difference is that the first equation shows a case where the distance traveled while executing the maneuver is based on the ***time*** required to make that maneuver (for example, the time to cross an intersection from a Stop), while the second equation shows a case where the distance traveled while executing the maneuver is based directly on the ***distance*** required to complete the maneuver (for example, braking distance for an emergency stop). For both forms of this general equation, vehicle speed (V) influences the second (MT) component.

The general form of the sight distance equation is:

$d_{SD} = kVt_{prt} + kVt_{man}$, where maneuver time is input or

$d_{SD} = kVt_{prt} + d_{manV}$, where maneuver time is input

Where:

d = required sight distance
V = velocity of the vehicle(s)
t_{prt} = PRT
t_{man} = MT
d_{manV} = distance required to execute a maneuver at velocity V
k = a constant to convert the solution to the desired units (feet, meters)

Tutorial 3: Detailed Task Analysis of Curve Driving

A task analysis of the different activities that drivers must conduct while approaching and driving through a single curve (with no other traffic present) was conducted to provide qualitative information about the various perceptual, cognitive, and psychomotor elements of curve driving. Consistent with established procedures for conducting task analyses (Campbell and Spiker, 1992; Richard, Campbell, and Brown, 2006; McCormick, 1979; Schraagen, Chipman, and Shalin, 2000), the task analysis was developed using a top-down approach that successively decomposed driving activities into segments, tasks and subtasks. The approach used in this tutorial was specifically based on the one described in Richard, Campbell, and Brown (2006); readers interested in additional details about the methodology should consult that reference (available at http://www.tfhrc.gov/safety/pubs/06033/).

The curve driving task was broken down into four primary segments, with each segment generally representing a related set of driving actions (see Figure 22-8). The demarcation into segments was primarily for convenience of analysis and presentation and does not imply that the curve driving task can be neatly carved up into discrete stages. Within each segment, the individual tasks that drivers should or must perform to safely navigate the curve were identified. Moreover, these driving tasks were further divided based on the information-processing elements (perceptual, cognitive, and psychomotor requirements) necessary to adequately perform each task. The perceptual requirements typically refer to the visual information about the curve and the surrounding roadway that drivers need to judge the curvature, determine lane position and heading, etc. The cognitive requirements typically refer to the evaluations, decisions, and judgments that drivers have to make about the curve or the driving situation. The psychomotor requirements refer to the control actions (e.g., steering wheel movements, foot movements to press brake, etc.) that drivers must make to maintain vehicle control or to facilitate other information acquisition activities.

The task analysis presented in Table 22-6 shows the driving tasks and corresponding information-processing subtasks associated with driving a typical horizontal curve, approaching from a long tangent. Drivers must also engage in other ongoing safety-related activities, such as scanning the environment for hazards; they may also engage in in-vehicle tasks such as adjusting the radio, using windshield wipers, or consulting a navigation system (just to name a few). However, these more generic tasks are not included in the task analysis in order to emphasize those tasks and subtasks that are directly related to curve driving.

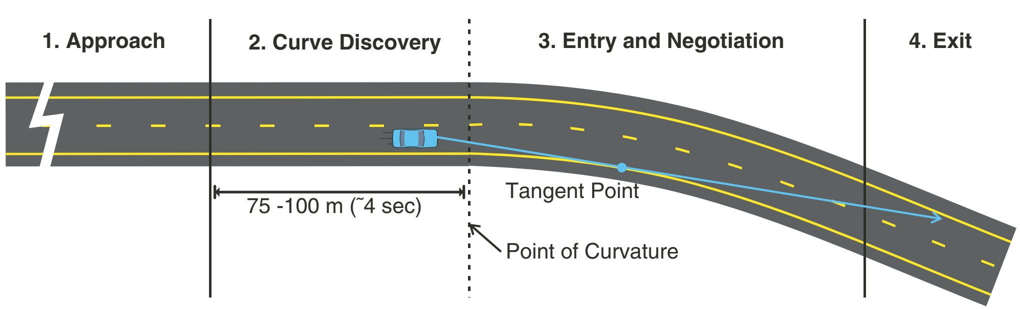

Figure 22-8. The four primary segments of the curve driving task.

Table 22-6. Driving tasks and information-processing subtasks associated with a typical curve.

Driving Task	Perceptual Requirements	Cognitive Requirements	Psychomotor Requirements
1. Approach			
1.1 Locate bend	Inspect forward roadway scene for evidence of bend	Recognize visual cues indicating departure from straight path	Eye movements needed for scanning
1.2 Get available speed information from signage	Visually scan environment for signage	Read and interpret sign information	Head and eye movements needed for scanning
1.3 Make initial speed adjustments	Look at speedometer	Read speedometer information and compare to posted speed	Execute necessary foot movements to achieve desired speed change
2. Curve Discovery			
2.1 Determine curvature	Look at roadway and environment features at curve location	Estimate curve angle based on visual image and experience	Head and eye movements needed for scanning
2.2 Assess roadway conditions (e.g., low friction, poor visibility)	Look at roadway in front of vehicle	Determine conditions requiring (additional) speed reductions	Execute necessary foot movements to achieve desired speed change
2.3 Make additional speed adjustments	Look at speedometer and/or view speed cues from environment	Read speedometer and/or judge safe speed based on cues and experience	Execute necessary foot movements to achieve desired speed change
2.4 Adjust vehicle path for curve entry	Look at roadway/lane marking information in the immediate forward view	Determine the amount of steering wheel displacement required to achieved desired lane position	Head and eye movements needed for viewing, and precise arm movements for steering control
3. Entry and Negotiation			
3.1 Adjust speed based on curvature/lateral acceleration	Perceive lateral acceleration and look at roadway motion cues	Judge safe speed based on visual cues and experience or read speedometer	Execute necessary foot movements to achieve desired speed change
3.2 Maintain proper trajectory	Look at tangent point or intended direction	Determine amount of steering wheel displacement required to achieved desired heading	Head and eye movements needed for scanning, and precise arm movements for steering control
3.3 Maintain safe lane position	Look at roadway/lane marking information in the immediate forward view	Determine amount of steering wheel displacement required to achieved desired lane position	Head and eye movements needed for viewing, and precise arm movements for steering control
4. Exit			
4.1 Accelerate to appropriate speed	Look at speedometer and/or view speed cues from environment	Read speedometer and/or judge safe speed based on cues and experience	Execute necessary foot movements to achieve desired speed change
4.2 Adjust lane position	Look several seconds ahead down the roadway	Determine amount of steering wheel displacement required to achieved desired heading	Head and eye movements needed for scanning, and precise arm movements for steering control

The primary source of information for segment tasks was the comprehensive driving task analysis conducted by McKnight and Adams (1970); however, other research more specifically related to curve driving were also used:

- Donges, E. (1978). Two-level model of driver steering behavior. *Human Factors, 20*(6), 691–707.
- Fitzpatrick, K., Wooldridge, M. D., Tsimhoni, O., Collins, J. M., Green, P., Bauer, K. M., Parma, K. D., Koppa, R., Harwood, D. W., Anderson, I., Krammes, R. A., and Poggioli, B. (2000). *Alternative Design Consistency Rating Methods for Two-Lane Rural Highways.* Final Report. (FHWA-RD-99-172). McLean, VA: FHWA.

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- Krammes, R. A., Brackett, R. Q., Shafer, M. A., Ottesen, J. L., Anderson, I. B., Fink, K. L., Collins, K. M., Pendleton, O. J., and Messer, C. J. (1995). *Horizontal Alignment Design Consistency for Rural Two-Lane Highways.* Final Report. (FHWA-RD-94-034). McLean, VA: FHWA.
- McKnight, A. J., and Adams, B. B. (1970). *Driver Education Task Analysis. Volume I. Task Description.* (DOT HS 800 367). Washington, DC: National Highway Traffic Safety Administration.
- Pendleton, O. J., and Messer, C. J. (1995). *Horizontal Alignment Design Consistency for Rural Two-Lane Highways.* Final Report. (FHWA-RD-94-034). McLean, VA: FHWA.
- Richard, C. M., Campbell, J. L., and Brown, J. L. (2006). *Task Analysis of Intersection Driving Scenarios: Information Processing Bottlenecks* (FHWA-HRT-06-033). Washington, DC: FHWA. Available at http://www.tfhrc.gov/safety/pubs/06033/
- Salvendy, G. (Ed.). (1997) *Handbook of Human Factors and Ergonomics* (2nd ed.). New York: Wiley.
- Serafin, C. (1994). *Driver Eye Fixations on Rural Roads: Insight into Safe Driving Behavior.* (UMTRI-94-21). Ann Arbor: University of Michigan Transportation Research Institute.
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- Vaniotou, M. (1991). The perception of bend configuration. *Recherche Transports Securite,* (7), 39–48.

For the most part, these references and the other research provided information about which tasks were involved in a given segment, but not complete information about the specific information-processing subtasks. To determine this information, the details about the information-processing subtasks and any other necessary information were identified by the authors based on expert judgment and other more general sources of driving behavior and human factors research (e.g., Groegor, 2000; Salvendy, 1997; Underwood, 1998).

CHAPTER 23

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Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation