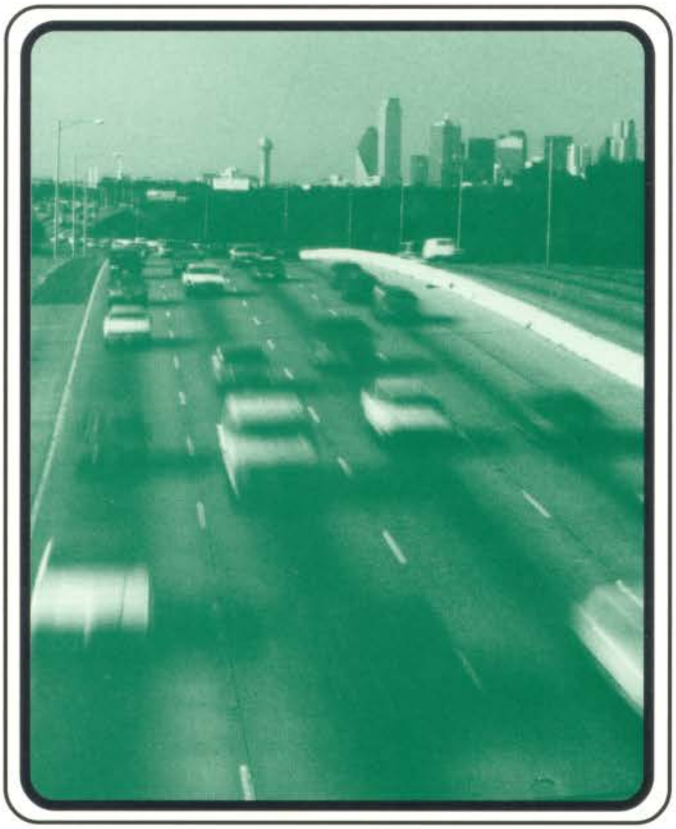
SPEED

Understanding design, operating, and posted speed



Report No. 1465-1

Sponsored by
Texas Department of Transportation
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Federal Highway Administration

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Disclaimer

CONTENTS

LIST OF FIGURES

How fast you think you can drive safely sometimes differs from what is posted on the speed limit sign. Also, individual drivers often disagree about how fast is "too fast." Questions such as "Should I slow down to 30 mph for that curve?" and "Why should I have to limit my speed on a four-lane straight and flat roadway with no traffic?" are frequently asked. These are questions and concerns that transportation engineers must consider and often explain as they design and operate our roadways.

Research and experience reveal new ways of improving safety and efficiency, and also teach what works best. It's important for engineers and policy makers to have access to the most technically accurate and current information, so they can accurately explain how roadways are designed and operated, as well as ensure that official documents continue to evolve and improve.

This document was prepared to aid transportation engineers in explaining speed-related concepts. It compiles and reviews the current definitions of key speed-related terms. It also discusses appropriate relationships and practice pertaining to these key speed measures.

DEFINING SPEED

Definitions and assumptions about speed are among the elements of The American Association of State Highway and Transportation Officials' (AASHTO) design policy that have evolved over time. AASHTO compiles and publishes *A Policy on Geometric Design of Highways and Streets* (1), which individual states either adopt or adapt for use as their design manual.

At present, some of the definitions that have been modified in practice have not yet been adopted as revisions to official document definitions. This natural evolutionary process sometimes puts practicing engineers in an uncomfortable position when they have to explain their decisions to citizens. The following sections provide an overview of current and past definitions and interpretations of the various types of speed.

Design Speed

The original definition of design speed (coined in 1938) was "the maximum approximately uniform speed which probably will be adopted by the faster group of drivers but not, necessarily, by the small percentage of reckless ones" (2). The concept was introduced so that an appropriate speed, based upon the reasonable desires of the majority of drivers, could be selected, and then all highway geometry features designed to accommodate that speed.

AASHTO's current definition of design speed is "the maximum safe speed that can be maintained over a specified section of highway when conditions are so favorable that the design features of the highway govern" (1). The definition has clearly become more abstract, even though the basic concept is the same. As a result, care must be taken in interpreting the current design speed definition. Furthermore, geometric design practitioners and researchers are currently discussing possible changes in how design speed is defined and applied. Ideally, changes will more accurately reflect our experience and understanding about the appropriate meaning and use of design speed.

Operating Speed

Operating speed is a good example of a term whose official definition has not kept up with the more relevant definition used in practice. Current design policy documents define operating speed as "the highest overall speed at which a driver can travel on a given highway under favorable weather conditions and under prevailing traffic conditions without at any time exceeding the safe speed as determined by the design speed on a section-by-section basis" (1). This definition is difficult to interpret and has little practical meaning or use. As a result, it is rarely used in practice.

In current practice, the term *operating speed* refers to the speed at which drivers are observed operating their vehicles. The 85th percentile of a sample of observed speeds is the most frequently used descriptive statistic for the operating speed associated with a particular location or geometric feature.

85th Percentile Speed

The 85th percentile speed is the speed at or below which 85 percent of drivers are operating their vehicles. Researchers generally perform spot speed studies to obtain reliable estimates of 85th percentile speeds. In these studies, a speed measurement location is identified on a highway, and speeds are measured for an adequate sample of free-flowing vehicles (typically 100–125). The term "free-flowing" means that drivers are not impeded by other vehicles and, therefore, are assumed to be operating at their desired speed at the measurement location. As illustrated in Figure 1, speeds recorded at a given location typically fit a normal distribution (i.e., bell-shaped curve). A variety of equipment may be used to measure speeds, including radar speed meters, laser speed meters, and other devices that use on-pavement sensors to measure the time it takes vehicles to travel a known distance.

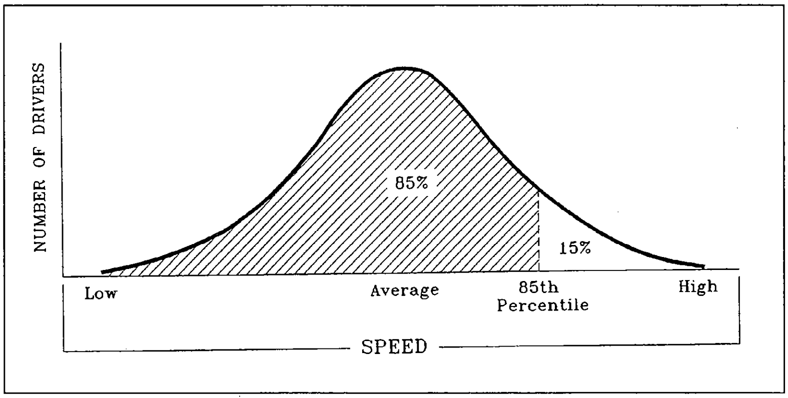

Figure 1. *Normal Distribution of Speeds. The 85th percentile speed is the speed at or below which 85 percent of drivers are operating.*

Posted Speed

Posted speed refers to the maximum speed limit posted on a section of highway using the regulatory sign illustrated in Figure 2. The Texas Department of Transportation's Procedure for Establishing Speed Zones states that the posted speed "should be based primarily upon the 85th percentile speed when adequate speed samples can be secured" (3). Although, speed zoning guidelines permit consideration of other factors (including roadside development, road and shoulder surface characteristics, and pedestrian and bicycle activity), basing posted speeds strictly upon measured 85th percentile speeds has been standard practice both in Texas and nationwide. Speed limits cannot be posted in excess of legislatively mandated speed limits. From 1974 to 1995, the U.S. Congress also imposed the 55 mph National Maximum Speed Limit. In 1995, Congress repealed the National Maximum Speed Limit and returned control of maximum speed limits to the states. Texas, for example, has a 70 mph maximum speed limit.

Figure 2. *A regulatory speed limit sign.*

Selecting Design Speed for a Highway

It seems reasonable that highways should be designed to accommodate the speeds at which drivers want to travel. Indeed, AASHTO's current highway design policy states that basic principle:

> "The speed selected for design should fit the travel desires and habits of nearly all drivers. [In other words, the design speed should be] nearly all inclusive of the typically desired speeds of drivers, where this is feasible" (1).

However, in selecting an appropriate design speed for a section of highway, it is important to understand two qualifiers related to the above design speed policy.

1) "nearly all drivers"—It would not be practical to accommodate the desired speed of all drivers, because some drivers' desires are unreasonably fast. For example, although it may be contrary to the desires of some drivers, it is inappropriate to design streets in residential areas for high speeds. Therefore, to be reasonable, the qualification "nearly all drivers" is specified.

2) "where this is feasible"—This qualification recognizes that many factors in addition to speed influence the design of a highway and may have overriding importance in highway design decisions. Terrain, development, the environment and other issues may make a design that would accommodate the desires of nearly all drivers either very costly or otherwise unacceptable. For example, designers may want to flatten a sharp curve on a rural highway in order to provide a higher design speed, but doing so may not be feasible if it would encroach on a mountain, river, or other natural feature in an environmentally sensitive area.

Applying Design Speed to Highway Design

After a design speed is chosen, it influences several other design decisions, including how flat a curve or a hill crest should be. Design speed also influences lane and shoulder widths, roadside clearances, and drainage structures (for example, whether it is appropriate to use curb and gutter or open ditches). Associated with each design speed are specific values for horizontal curvature sharpness and the minimum distance ahead visible to drivers. These values are based upon laws of physics and conservative assumptions about driver, vehicle, and roadway characteristics. That is, the assumptions provide considerable margins of safety. The following sections provide a general explanation of how design speed is considered in horizontal and vertical curve design.

Design Speed and Horizontal Curves

Background: As Figure 3 shows, horizontal curves are circular arcs—i.e., a curve to the left or right—that connect straight sections of highway. On a horizontal curve, the design speed is used to determine acceptable ranges for the sharpness of curvature and how much the pavement surface is banked (superelevated). The sharpness of a curve is measured by the radius of curvature (the shorter the radius, the sharper the curve). Figure 4 illustrates this concept. How much the pavement surface on the curve is banked is measured by the superelevation rate (the change in elevation from the inside to the outside edge of the pavement per unit change in pavement width). Figure 5 illustrates this concept. Typically, superelevation rates (e) are no more than 4 to 6 percent in urban areas or 8 to 10 percent in rural areas.

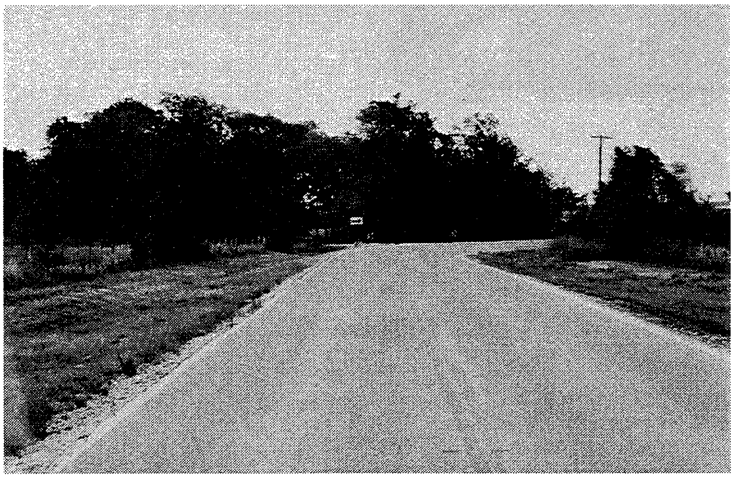

Figure 3. *A Horizontal Curve.*

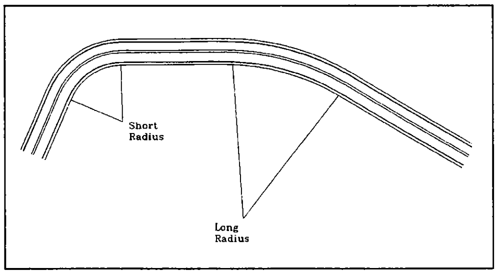

Figure 4. *Plan View of a Horizontal Curve.*

Why Horizontal Curves Are Banked: Curves are banked (superelevated) so that the gravitational force associated with the weight of the vehicle can also help counteract the centrifugal force and, thereby, reduce the frictional force required to keep the vehicle from sliding out of the curve. A brief refresher course on basic physics may help explain this concept:

Centrifugal force acts on any object traveling a circular path. Consider holding a bucket of water by the handle and spinning around in a circle. The force you feel pulling the bucket out of your hands is centrifugal force. The faster you spin the bucket, the greater the centrifugal force and, therefore, the more tightly you need to grasp the handle to hold onto the bucket. The same principal applies in driving around a horizontal curve—the faster you drive around the curve, the greater the centrifugal force acting on the vehicle. The frictional force between the vehicle's tires and the pavement surface counteracts the centrifugal force to keep the vehicle on the road.

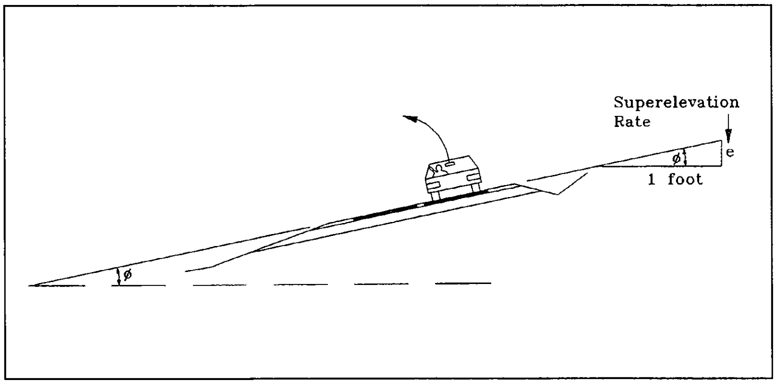

Figure 5. *Cross Section of a Banked (i.e., superelevated) Horizontal Curve.*

The maximum side friction for design purposes is controlled by the "seat-of-the-pants" concept. That is, in most cases, drivers (or passengers) would feel that they are about to slide on the car seat before the vehicle's tires would start slipping on the pavement surface. Figure 6 illustrates this concept. The maximum side friction values that control the design speed of a horizontal curve are set to avoid this feeling of discomfort. The values currently used are based upon experiments conducted in the 1940s in which blindfolded passengers were driven around curves at various speeds and asked to indicate the speed at which they started feeling discomfort. Use of this "seat-of-the-pants" criterion provides considerable margin of safety in design.

The maximum values for side friction and superelevation rate are combined to determine the sharpest curve (minimum radius) allowed for a given design speed. Designers, however, use flatter curves wherever possible.

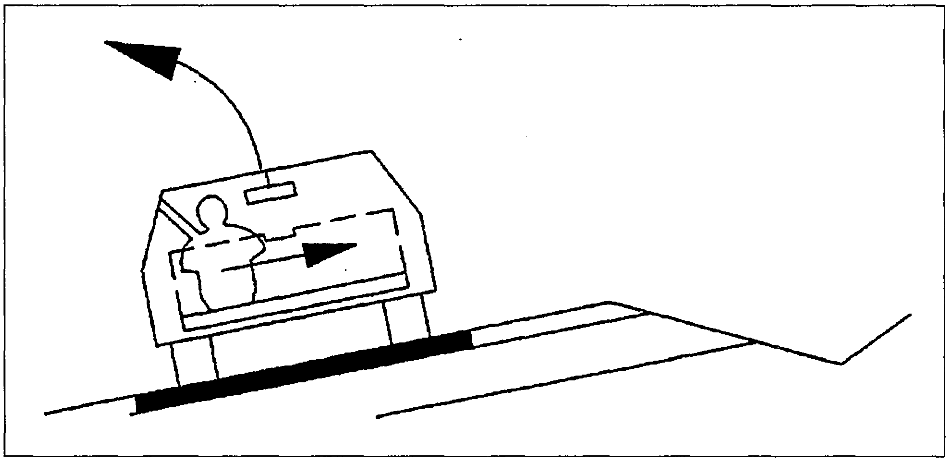

Figure 6. *The "seat of the pants" interaction between centrifugal and gravitational forces.*

Design Speed and Vertical Curves

Background: A vertical curve is a hill crest, as shown in Figure 7, or a sag, as shown in Figure 8. On a vertical curve the design speed determines the available sight distance (i.e., the length of roadway visible to the driver). At a minimum, vertical curves are designed so that a driver operating at the design speed can react and brake to a stop on wet pavement within the length of roadway visible. At higher design speeds, it takes longer to stop a vehicle; therefore, vertical curves must be longer and flatter to provide sight distance.

Figure 7. *A Crest Vertical Curve.*

Measuring Sight Distance over a Hill Crest: Figure 9 illustrates how sight distance over a hill crest is measured. For a given design speed the required sight distance is based upon assumptions about 1) how long it takes drivers to brake in an emergency stop before striking a high stationary object on the roadway and 2) the frictional force that can be generated between vehicles' tires and the pavement surface. The assumed time for perception and brake reaction is 2.5 seconds—more than enough time for almost all drivers in almost all situations. The assumptions about the available frictional force are based upon a near-worst case scenario—drivers locking their brakes (which, of course, they shouldn't) and skidding to a stop on a wet pavement. Actually, braking distances are shorter when the pavement is dry, when drivers pump (rather than lock) their brakes, or when a vehicle has antilock brakes. These assumptions combine to provide considerable margins of safety in design.

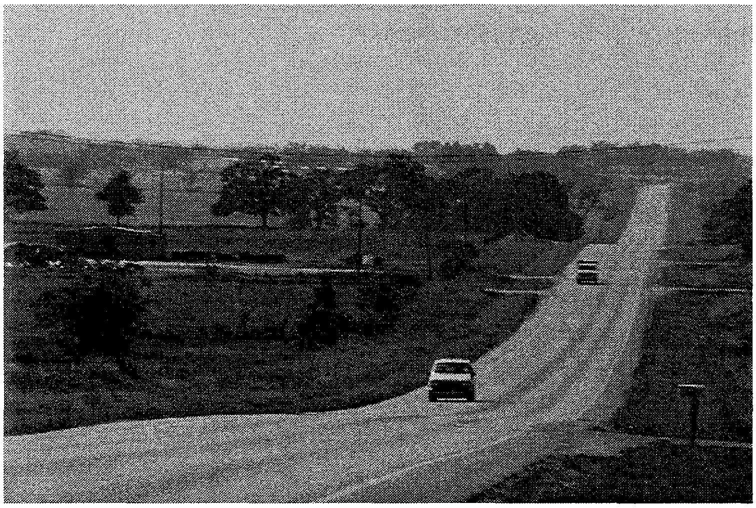

Figure 8. *A Sag Vertical Curve.*

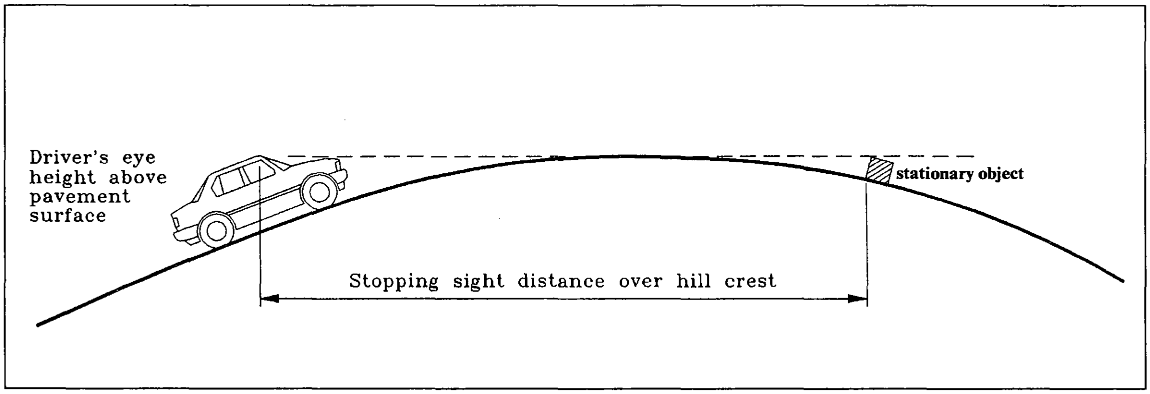

Figure 9. *Measurement of Sight Distance over a Crest Vertical Curve.*

Selecting Posted Speed for a Highway

The posted speed (shown in 5 mph increments, e.g., 30, 35, 40) is generally obtained by rounding the 85th percentile speed to the nearest speed value in miles per hour that ends in 5 or 0. Using the 85th percentile speed in selecting posted speeds is based upon the belief that the large majority of drivers

- are capable of judging appropriate speeds based upon the roadway geometry, roadside development, weather conditions, traffic, etc., and
- operate at speeds that are reasonable and prudent.

Basing posted speeds upon 85th percentile speeds also promotes uniformity among speeds at a given location (i.e., it keeps the bell-shaped curve in Figure 1 tall and thin). The benefit of a uniform speed is that vehicle collisions are less likely to occur if drivers are traveling at about the same speed.

Applying Posted Speed in Highway Operations

Exceptions to the 85th Percentile Procedure

There have been two principal exceptions to the 85th percentile speed procedure.

1) On sections of highway with high accident experience, the posted speed may be as much as 7 mph lower than the 85th percentile speed.

2) National or state maximum speed limits prohibit higher posted speeds, even when the 85th percentile speed is higher.

There are concerns that, except in cases where safety makes it necessary, posting speeds below the 85th percentile speed puts the majority of drivers in violation, places unnecessary burdens on law enforcement personnel in arbitrarily selecting who should be ticketed, leads to a lack of credibility of speed limits, and leads to the use of large tolerances adopted by enforcement agencies.

Advisory Speed Panels on Sharp Curves

At locations where drivers may have difficulty judging appropriate speeds, warning signs, sometimes accompanied by advisory speed panels, are typically provided. Figure 10 shows a common example of an advisory speed panel with a curve warning sign. This sign is used to warn drivers that they are approaching a horizontal curve on which they should travel at a speed lower than the posted regulatory speed. The advisory speed corresponds to the maximum side friction values used to limit driver discomfort on curves (see p. 10). Many drivers exceed advisory speeds. This indicates that they accept the discomfort brought on by side friction values higher than our current design policy assumes.

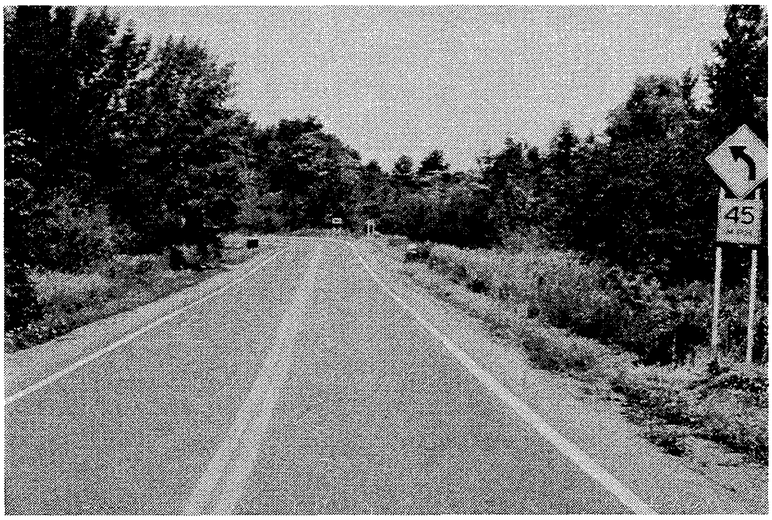

Figure 10. *A Curve Warning Sign with an Advisory Speed Panel.*

Is design speed the maximum safe speed?

The Theory

In theory, the design speed, operating speeds, and posted speeds on a roadway should be similar. That is, we select the design speed of a highway to accommodate the desires of most drivers. Therefore, after the highway is designed and constructed, we would expect to measure operating speeds similar in magnitude to the design speed. Since posted speeds are based upon 85th percentile operating speeds, we would also expect posted speeds and design speeds to be similar in magnitude. Unfortunately, as the previous discussions reveal, today's world just isn't that simple.

The Reality

In recent years, a number of studies have observed 85th percentile operating speeds higher than design speeds on both horizontal and vertical curves on rural two-lane highways, suburban arterial streets, and urban residential collector streets. This confirms the need for an answer to the following questions:

- Is it safe for operating speeds to be higher than a highway's design speed, i.e., "the maximum safe speed that can be maintained over a specified section of highway when the design features of the highway govern"?

- Is it safe and appropriate to post speed limits based upon 85th percentile operating speeds when they are higher than the design speed of a highway?

The following sections present answers to these questions based on research and current practice examined in this study.

The Answers

A cursory look at the official definitions of design speed, operating speed, and posted speed might lead one to conclude that any speed higher than a highway's design speed (i.e., the "maximum safe speed" for which that highway is designed) is inherently unsafe. In-depth consideration of the definitions and their applications in current practice, and of accident experience, however, does not support this conclusion.

As explained above, design speed fixes the sharpness of horizontal and vertical curvature. The criteria for what is "safe" at a given design speed are based upon comfort considerations and near-worst case conditions (e.g., 1940s vehicles and locked-wheel braking on wet pavements). These criteria include considerable margins of safety. Because of these built-in safety factors, exceeding the design speed is not necessarily unsafe. Furthermore, AASHTO highway design policy states that "above-minimum design values should be used where feasible" (1). In fact, many highway features have above-minimum designs, and the design speed may actually apply only to a small number of critical features. As a result, most curves and hill crests are flatter than would be necessary to accommodate a given design speed. As a result, the design speed of a highway (as stated on the highway's plans or other official documents) is likely to underestimate the "maximum safe speed" along most of that highway by any reasonable criteria for establishing what is "safe."

In most cases, it is appropriate to assume that for the large majority of drivers, speed selection is reasonable and prudent, and the associated risk they assume is not excessive, even if their operating speed is somewhat higher than the highway's design speed.

There are exceptions to these general conclusions. Operating speeds notably greater than average (in the extreme upper tail of the distribution shown in Figure 1) may use most of the margins of safety in design. Since neither design speeds nor posted speed limits accommodate the full range of adverse weather conditions (including ice, snow, heavy rain, and fog), drivers should adjust their speed to such conditions. Furthermore, the hazards associated with some highway features may not be visible or apparent to unfamiliar drivers (for example, sharp curves or intersections beyond a hill crest); warning signs are typically installed at these locations. So while operating speeds higher than a highway's design speed cut into margins of safety, what remains is still more than adequate for most situations.

In general, while large differences between design and operating speeds may be a problem, small differences are not a problem.

Summary

A highway's design speed incorporates considerable margins of safety. Although excessive operating speed may use most of the margins of safety, it is likely that the speeds exhibited by the large majority of drivers are reasonable and prudent. Therefore, 85th percentile operating speeds higher than a highway's design speed should not be surprising and are not necessarily unsafe. Posted speeds that correspond to 85th percentile operating speeds are generally appropriate, even where they are higher than the highway's design speed, because they promote uniformity of speeds, which has attendant safety benefits.

16 REFERENCES

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