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Sag Vertical Curve Design Criteria for Headlight Sight Distance

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DETAILS

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Dr. Ronald B. Gibbons, Director of the CIBSS, was the Project Director and Principal Investigator. The other authors of this report are Alejandra Medina, Senior Research Associate with VTTI and co-Principal Investigator; Dr. Hesham A. Rakha, P.Eng, Director of the Center for Sustainable Mobility at VTTI and Professor with the College of Civil & Environmental Engineering at Virginia Tech, and co-Principal Investigator, Brian Williams, Research Specialist Senior with CIBSS; and Jianhe Du, Research Associate with the Center for Sustainable Mobility at VTTI. The work was done under the general supervision of Dr. Gibbons.

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ABSTRACT

This document is the final report for NCHRP Project 15-41, "Sag Vertical Curve Design Criteria for Headlight Sight Distance." This report includes a review of the current methodologies used in the design of sag vertical curves, a review of the changes in headlamp technologies, the results of the survey of practitioners, two visibility experiments, and discussion on potential changes to the American Association of State Highway and Transportation Officials (AASHTO) design guide.

The review of the headlamp technology shows that, over time, headlamp technologies have had increasing limitation on the amount of light emitted above the horizontal axis of the headlamp. In addition to the regulatory impact, headlamp technologies such as visually optically aligned technologies also limit uplight. In the practitioner survey, it was found that very few deviations from the AASHTO design methodologies were used. Based on the practitioner review, the potential to modify the current methodologies is limited to the manipulation of the vehicle speed, deceleration, and the angle of curvature change.

The results of the visibility experiments found that participants detected objects at distances which were significantly shorter than the safe stopping distance (SSD). This occurred not only in sag vertical curves, but also on flat roadway. This indicated that even if sag vertical curves were redesigned, visibility distance would still be shorter than SSD because the headlamps would be the limiting factor. A review of the potential modifications to sag vertical curve designs (which were suggested as a result of the practitioner survey) found that these changes would be inadequate to make up the difference between visibility distance and SSD.

CHAPTER 1 INTRODUCTION

The evolution of the typical vehicle headlamp has undergone a significant transition in recent years. Traditional headlamps were simply sealed-beam lamps, whereas modern headlamps are well-designed optical instruments that provide more effective light control than was previously attainable.

The transition of the headlamp to these new modern styles coupled with the new height of headlamps in larger profile vehicles has resulted in some significant changes to vehicle performance in the driving environment. The first change relates to general visibility. New headlamp designs have shown limited effects in pedestrian and object visibility (Blanco et al., 2005) and variability in sign visibility (Carlson and Hawkins, 2003). The most recent considerations that have been investigated are those of sag vertical curve design. Gogula (2006) and Hawkins (2007) have performed extensive evaluations of the performance of modern headlamps in sag vertical curves. In their research, they have determined that the current design criteria of sag vertical curves are not representative of existing technology.

As a vehicle approaches a sag vertical curve, the distance that the headlamps reach is limited by the road that rises on the other side of the curve relative to the vehicle's central axis. The greater the change in the gradient from one side of the curve to the other, and the shorter the overall curve distance, the more limited the headlamp performance. If a headlamp projects a greater amount of light above its horizontal axis, the limitations that impact the headlamp are minimized.

The AASHTO design requirements for sag vertical curves are based on four specifications: headlamp sight distance (SD), passenger comfort, drainage control, and general appearance. The headlamp SD requirements are based on a safe stopping SD that is perceived throughout the sag curve. The assumption used in the development of the requirements is that a 1-degree uplight limitation is evident in the headlamp. However, recent research on sag vertical curves and headlamps show that this limitation is likely no longer valid and that real-world performance from a modern headlamp does not meet the current design standards. These results have been developed in a theoretical manner and Gogula (2006) has attempted to valid them.

RESEARCH OBJECTIVE

This project considers the evaluation of the performance of modern headlamps in vertical sag curve conditions. There are three primary research objectives:

1) Evaluation of the impact of modern headlamp performance on the design of sag vertical curves;
2) Development of proposed changes to the criteria and guidance for the design of sag vertical curves based on the results of the visibility testing; and
3) If required, perform a cost analysis of the potential changes to the AASHTO policy.

To achieve these goals, the project team has undertaken a series of tasks which led to the final assessment of the AASHTO methods for the design of sag headlamps. The tasks described in this document include the literature review, a survey of practitioners, an assessment of the current methodologies, and consideration of headlamp performance.

CHAPTER 2 REVIEW OF CURRENT AASHTO METHODOLOGIES

The sag vertical curve requirements have not changed since 1965. The definition for the limits of sag vertical curves in the AASHTO guidelines in terms of length, speed, or grades is based on the assumption of a 1° uplight condition for headlamps (AASHTO, 2004).

For safety, vehicles traveling on a vertical curve should be provided with sufficient SD for a timely stop before hitting another car or object. When establishing lengths of sag vertical curves, four different criteria are recognized: passenger comfort, drainage control, general appearance, and headlight SD.

According to AASHTO (2004), the general expression for passenger comfort on a sag vertical curve is:

$$L = \frac{AV^2}{46.5} \tag{1}$$

Where L is the length of the sag vertical curve in feet; A is the algebraic difference in grades in percent; and V is the design speed in miles per hour (mph). AASHTO states that the length of vertical curve needed to satisfy this comfort factor is only about 50% of that needed to satisfy the headlight SD criterion; thus, this criterion will not be the emphasis of this report.

For drainage requirements, sag curve length will become an issue in Type III curves (shown in Figure 1) where the Vertical Point of Intersection (VPI) is the lowest part on the curve and curbed sections are used. AASHTO defines a maximum of 167 for K (ratio of curve length, L, to the algebraic difference in grade, A) in such situations. This criterion differs from other criteria in that it determines the maximum length of the curve.

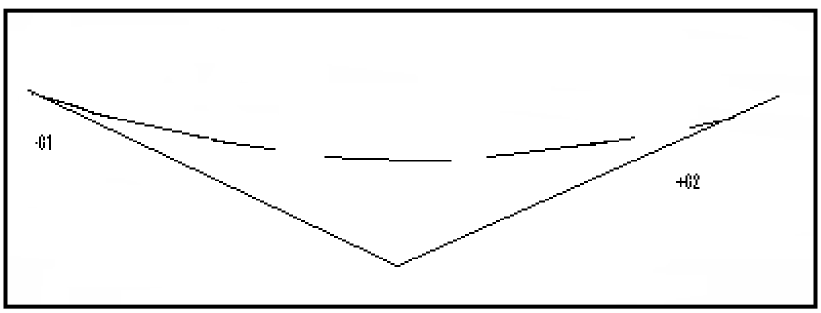


Figure 1. Type III sag vertical curve.

For general appearance of sag vertical curves, the rule-of-thumb for minimum curve length is $100 * A$. Also defined in AASHTO is a minimum length of vertical curves for flat gradients, which is $3 * V$. These two criteria are used to avoid curves that are too sharp or too short and are not directly related to the design modifications incurred by the evolution of headlamps.

The headlight SD, which is the portion of lighted highway ahead when a vehicle traverses a sag vertical curve at night, is the primary design control for sag curves. On a sag vertical curve, the SD during daytime is not an issue. However, when vehicles travel at night, the distance that drivers can detect is decided by headlight SD, which is shown as "Sight Distance S" in Figure 2.

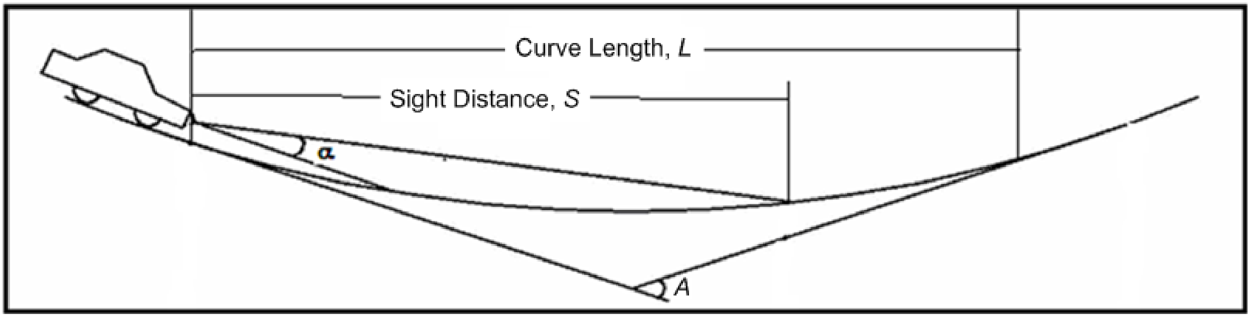


Figure 2. Sight distance and curve length on a sag curve.

Headlight SD is affected by the position of the headlights and the direction of the light beam. As stated in the current version of the AASHTO (2004) guidelines, a height of 600 mm (2 ft) and a 1-degree upward divergence of the light beam from the longitudinal axis of the vehicle are assumed when calculating SD. The equations used by AASHTO to calculate sag curve length:

When *S* (in feet) is less than *L* (in feet)

$$\boldsymbol{L = \frac{AS^2}{200[2.0 + S(tan1°)]}} \qquad \textbf{(2)}$$

When S (in feet) is greater than *L* (in feet)

$$\boldsymbol{L = 2S - \frac{200[2.0 + S(tan1°)]}{A}} \qquad \textbf{(3)}$$

Where *S* is the headlight SD (in feet), *L* is the length of a sag vertical curve (in feet), and *A* is the algebraic difference in grade (%). The headlight SD should be at least as long as the stopping SD for the driver to make a prompt stop when needed. In the equations above, Stopping Sight Distance (SSD) values are used in place of *S* with the assumption that a sag vertical curve should be long enough that the light beam distance is nearly the same as the SSD. SSD refers to the distance a vehicle travels from the instant the driver sees an obstacle that requires a stop, to the instant that the vehicle reaches a complete stop. The basic model for determining SSD was developed by AASHTO in 1940. This basic model consists of four parameters: design or initial speed, driver perception-reaction time, friction between the tires and the pavement, and percent grade. While these parameters have been revised several times since 1940, the basic model has remained the same (Fambro, Fitzpatrick, & Koppa, 1997).

As mentioned, the change in uplight angle in recent years caused a decrease in headlight SD. As shown in Figure 3, with a smaller upward divergence of the light from the axis of the vehicle, the point where the beam strikes the road surface is closer to the vehicle than before. To ensure the safety criterion is still met, modifications to the guideline need to be considered.

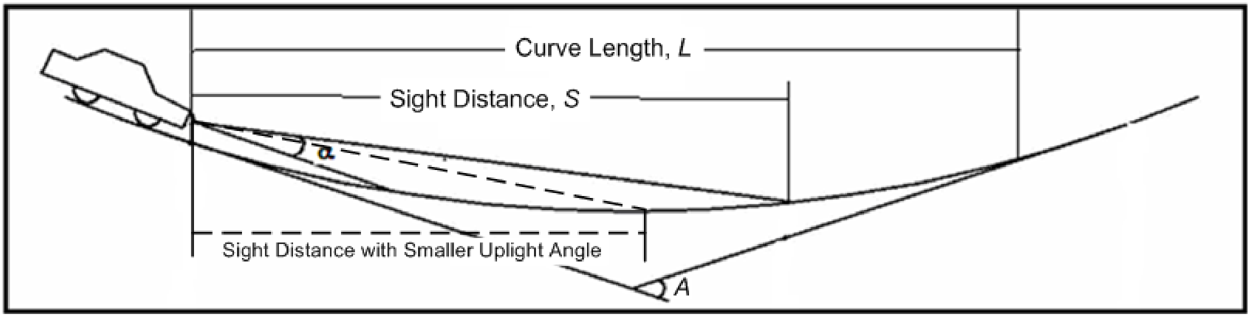


Figure 3. Sight distance and curve length on a sag curve.

CHAPTER 3 REVIEW OF HEADLAMP DESIGN

As SD is one of the limiting factors in the design of vertical curves it is the critical component which must be considered in the assessment of the sag curve design criteria.

For sag vertical curves, SD is limited to that which is allowed by the vehicle's headlamps. As mentioned, equations for determining the length of sag vertical curves assume a headlight that is 1 degree above horizontal (AASHTO, 2004). This value was likely determined using older sealed-beam headlamps which put out more light above horizontal than do modern replaceable-bulb headlamps. Since the development of these design equations, changing technology and efforts for the worldwide harmonization of headlamp standards has caused beam patterns to change drastically. Because of these changes, equations for sag vertical curves may be overestimating the SD allowed by modern headlamps.

EVOLUTION OF HEADLAMP DESIGN

In the United States, the first electric headlamps to be installed as standard equipment occurred in 1911. Electric headlamps installed as original equipment were not far behind in Europe, becoming standard on some vehicles in 1913 (as cited in Moore, 1998). These headlamps used a tungsten filament as the light source. Tungsten had two drawbacks, however. As the lights were operated, tungsten would boil off of the filament and would condense on the glass of the bulb, blackening it. Tungsten headlamps also produced relatively low light output for the power that they consumed. A tungsten filament bulb filled with nitrogen gas was first used on automobiles in 1915. The gas reduced the evaporation of the tungsten, slowing the blackening of the bulb, which allowed the filament to last longer (as cited in Moore, 1998).

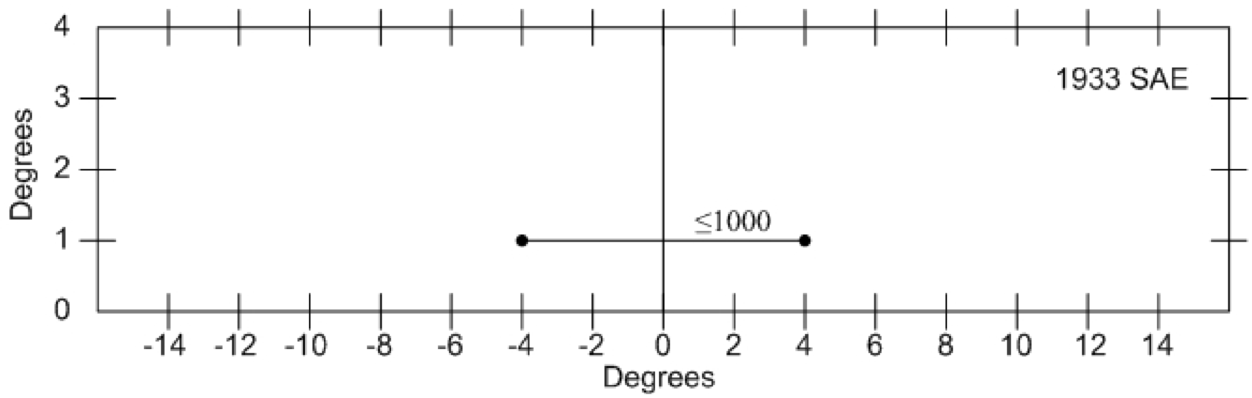
During the mid-1960s, the first halogen headlamps were used in Europe. Halogen headlamps use a tungsten filament in a bulb filled with halogen gases. The gases create a chemical reaction with the evaporating tungsten which redeposits the tungsten back onto the filament (Moore, 1998). This chemical reaction, known as the halogen cycle, increases the lifetime of the bulb, reduces blackening, and increases the light output relative to the power consumed. U.S. automobile manufacturers began installing halogen bulbs in sealed-beam headlamps in the 1970s (Moore, 1998). In Europe, regulators and manufacturers chose to use the extra efficacy of halogen bulbs to provide more light with the same power consumption. In the United States, most halogen bulbs produced the same amount of light as non-halogen bulbs, but with reduced power consumption.

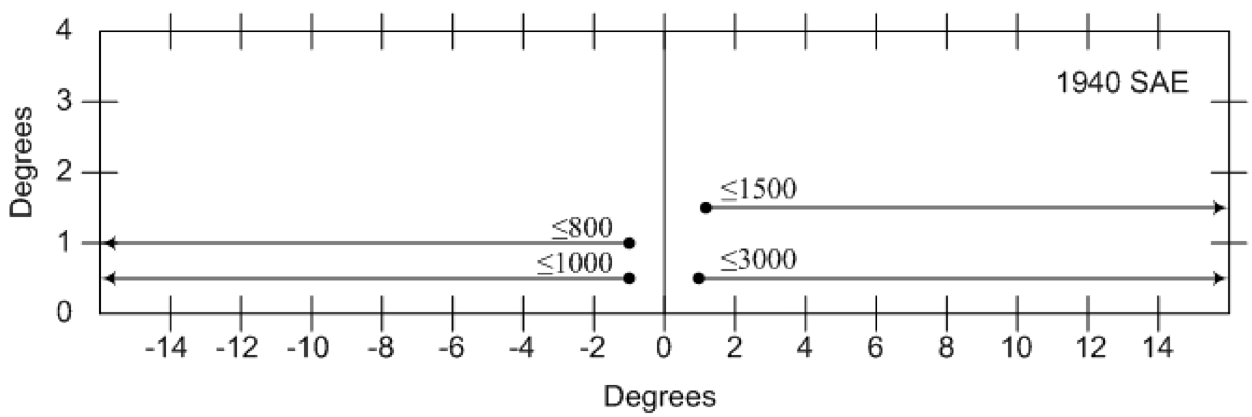
In the 1990s, another light source was introduced. High-intensity discharge (HID) headlamps were first offered as an option in Europe in 1991. HID headlamps, also known as "xenon headlamps," produce light with an electric arc. Metallic salts are vaporized within the arc, producing the lamp's high intensity. The xenon gas used in automotive HID allows the lamp to provide adequate light immediately upon powering on, and increases the speed at which the lamp reaches full brightness. HID lamps provide a light with a higher color temperature, which appears bluish-white as opposed to the yellowish light from tungsten filaments. They also provide longer life, increased light-source lumens, and higher intensity beam patterns than their halogen-tungsten counterparts (Moore, 1998).

Headlamps with light-emitting diode (LED) light sources were first installed in 2008 (Whitaker, 2007). Benefits of LED headlamps include a longer lifespan with slightly decreased power consumption. However, with multiple high-powered LEDs, temperature management becomes key. The heat from LEDs is produced at the rear of the emitters, and requires additional heat management measures such as heatsinks and cooling fans. In addition, because there is little heat from the front of the lights, ice and snow on the lens are not effectively thawed by the LEDs.

Headlamps have evolved due to two major factors: changing headlamp standards, and new technology. There are two major standards which regulate headlamps: the Society of Automotive Engineers (SAE) standards used in North America, and the Economic Commission for Europe (ECE) regulations used in much of the rest of the world. Historically, a major difference between these standards was the amount of light allowed above the horizontal axis of the headlamps; the prevailing ideas being increased visibility in SAE standards, and reduced glare in ECE regulations.

Figure 4 shows the amount of light allowed above horizontal according to several SAE regulations between 1933 and 1997. Included is the Federal Motor Vehicle Safety Standard (FMVSS) 108 , which incorporates SAE standards. A trend can be seen in which the light above horizontal has been generally decreasing (particularly left of the vertical) and also that the amount of light is becoming more regulated (i.e., more limits are imposed). The figures below only show the regulations pertaining to light above horizontal for the sake of simplicity.





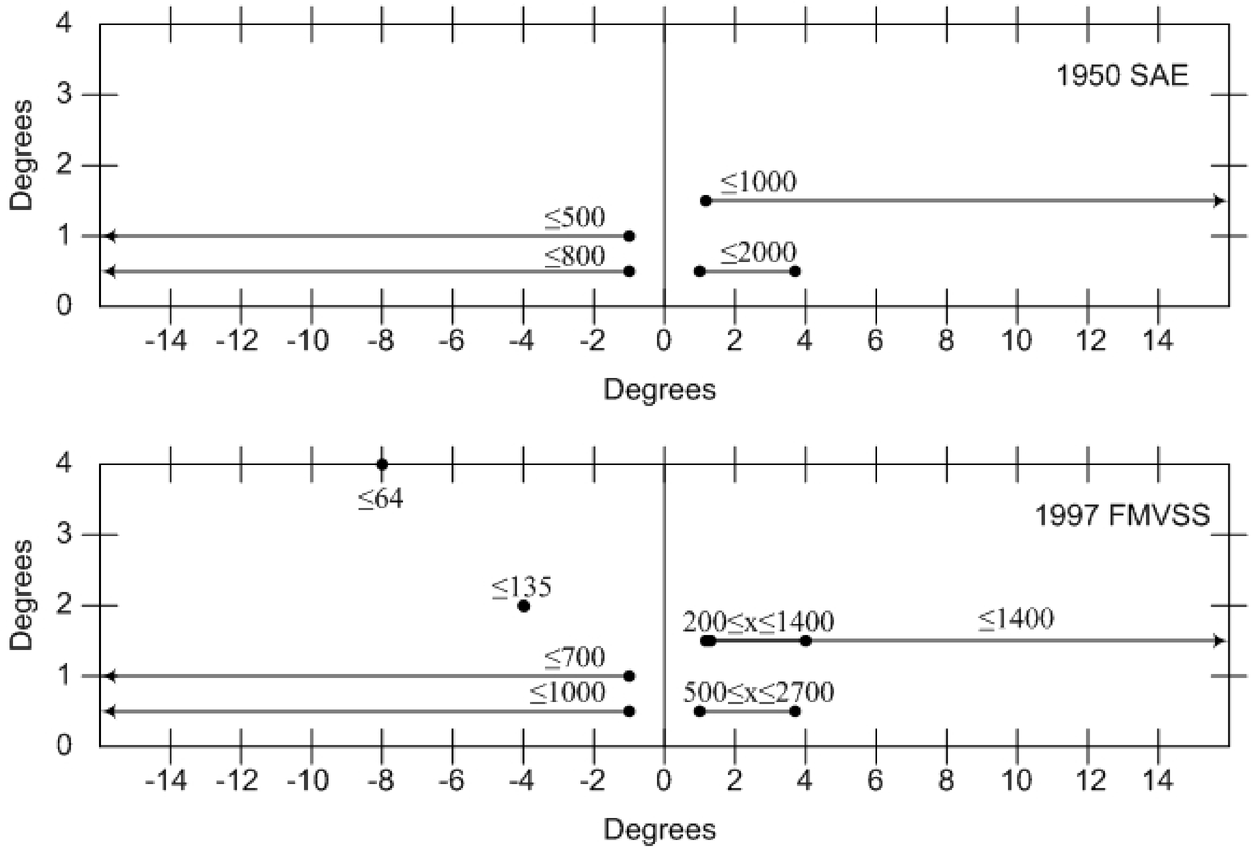


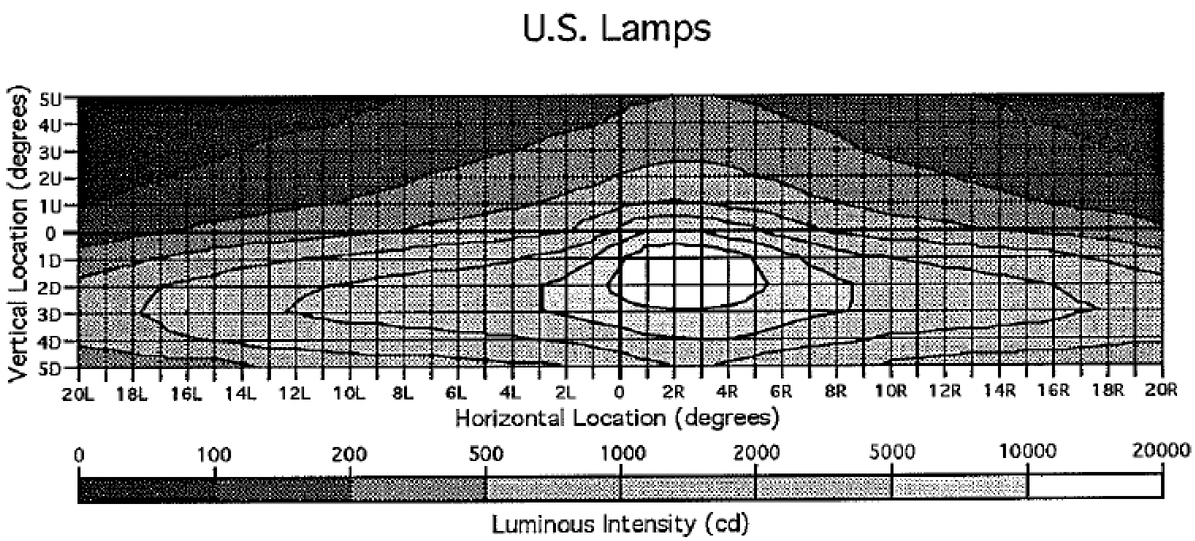
Figure 4. Light allowed above horizontal by SAE standards.

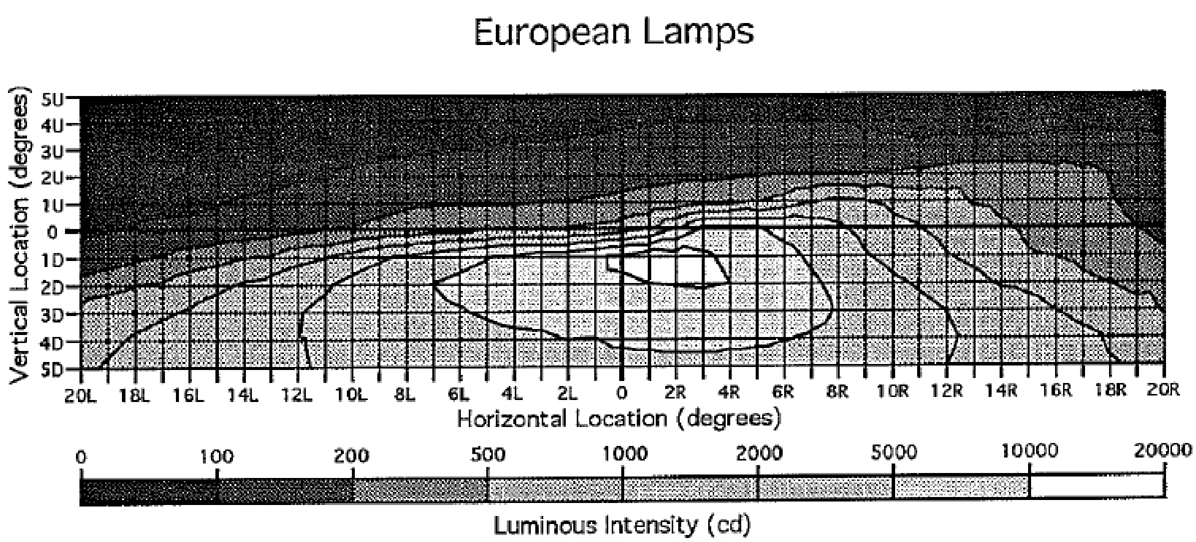
From this figure it can be seen that the regulations have changed. In 1940, the uplight was increased in both magnitude and angle, but was reduced again in 1950. An interesting addition was made in 1997 where a lower limit was placed on the uplight in order to ensure that the headlamp provided some uplight component.

Efforts to harmonize the disparate standards began in the mid-1900s, leading to the creation of an international group of lighting experts and vehicle manufacturers called the Groupe de Travail-Bruxelles 1952 (GTB). However, in spite of the research done at the time, the diametrically opposed philosophies of the SAE and ECE standards prevented a compromise on a common beam pattern (Moore, 1998). The greatest progress towards harmonization would come much later.

In 1990, the GTB was asked by the Group Rapporteurs Eclairage (GRE) to recommend one worldwide headlamp beam pattern (Moore, 1998). A study conducted by Sivak and Flannagan (1993) recommended four test points that should be common worldwide. The GTB took these four points, made slight modifications, and established the rest of the beam pattern in an attempt to make one unified beam pattern with improved illumination in the typical area of driver vision, sufficient illumination of road signs, and reduced glare for oncoming vehicles. However, the different priorities exhibited by North American and European standards prevented a compromise from being reached at the time (Moore, 1998).

In 1993, Sivak, Flannagan, and Sato conducted a study which measured the light output of 150 headlamps from the United States, Europe, and Japan. By taking the median output for each group, they were able to create isocandela diagrams of the "typical" headlamp for each region for the time period. As seen in Figure 5, the amount of light above horizontal is much higher for U.S. and Japanese SAE-J headlamps than for European and Japanese ECE-J headlamps. According to the study, the U.S. headlamps are representative of those manufactured in the late 1980s to early 1990s, and the European and Japanese headlamps are representative of those manufactured in the early- to mid-1980s.





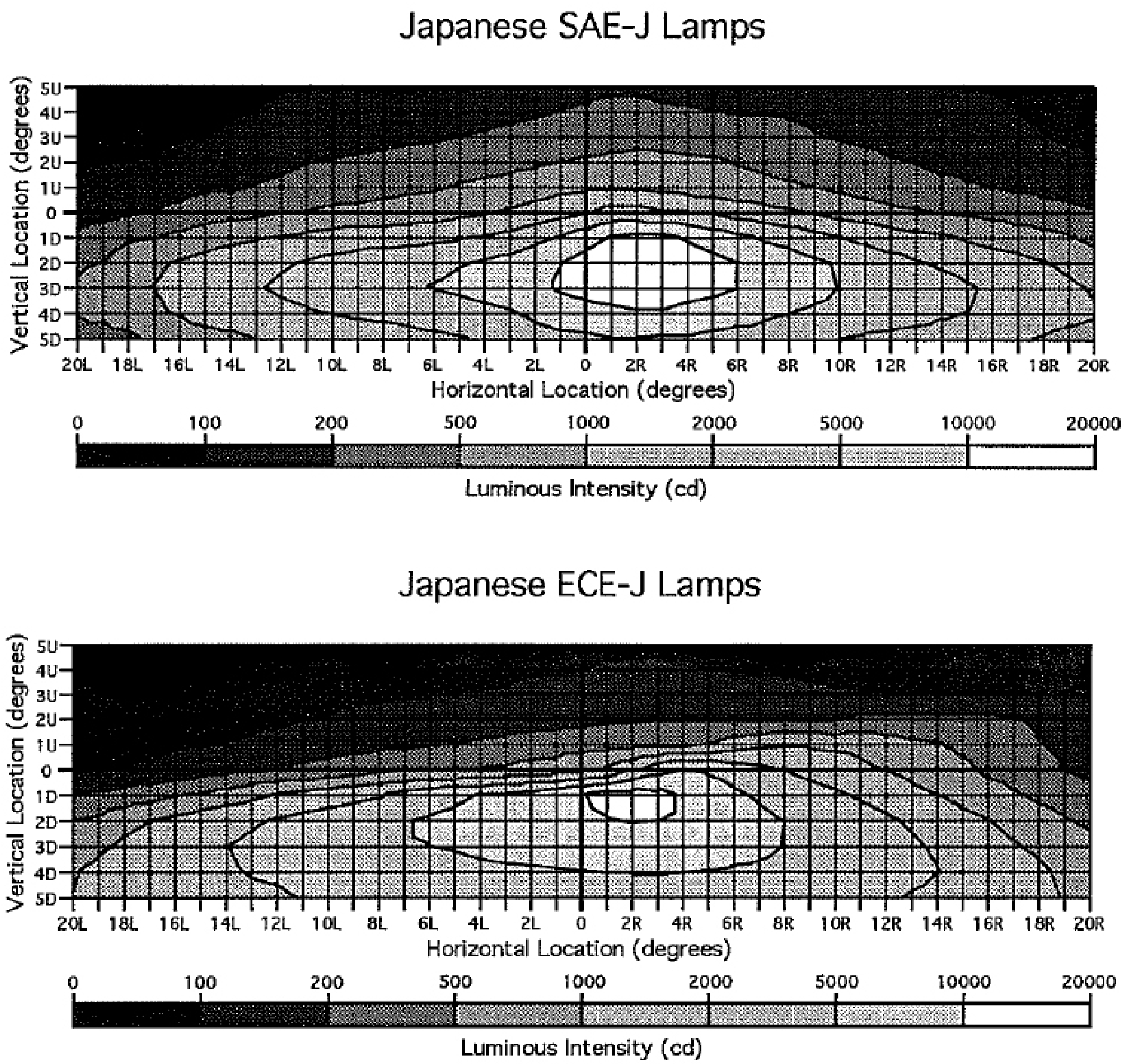


Figure 5. Isocandela diagrams of the median luminous intensities for U.S. headlamps, European headlamps, the Japanese SAE-J headlamps, and the Japanese ECE-J headlamps (Source: Sivak, Flannagan, and Sato, 1993).

Despite the apparent differences of the two standards in the diagrams, compromises have been made by both sides to bring headlamp beam patterns closer together.

In 1997, a large step towards harmonization was taken when FMVSS 108 was updated to include the option of labeling headlamps as visually/optically aimable (VOA). In order to be labeled as VOA, headlamps are required to have a steeper vertical gradient than conventional U.S. headlamps. There are two types of VOA headlamps: those aimed using the vertical gradient to the left of vertical (VOL) which are conceptually similar to European headlamps, and those aimed using the gradient to the right of vertical (VOR) which are conceptually similar to conventional U.S. headlamps (Sivak, Flannagan, & Miyokawa, 2000). Figure 6 shows the beam pattern and aiming points for VOR and VOL headlamps (HAP).

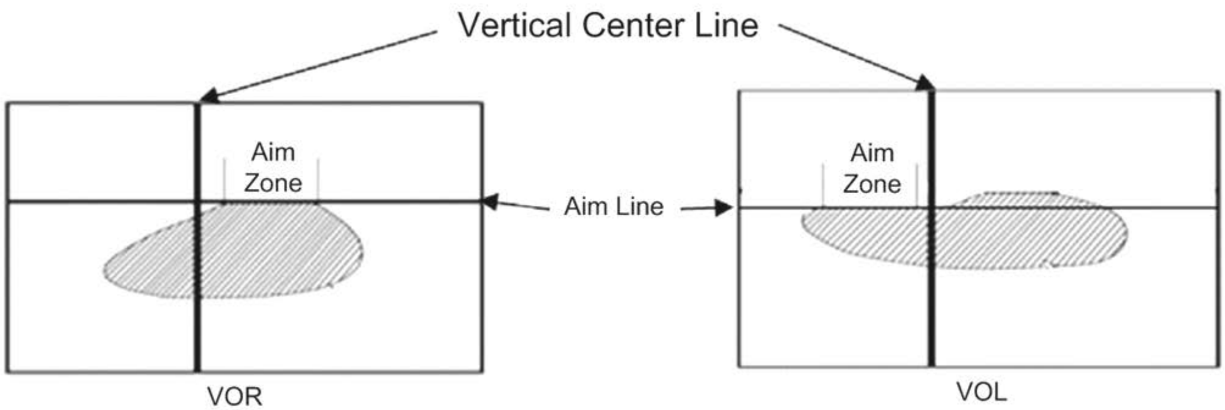


Figure 6. Beam patterns and aiming positions for VOR and VOL headlamps (Source: Headlamp Aiming Procedure, 2006).

Another major step toward complete harmonization was made in 1999, when the GTB proposed a fully harmonized beam pattern to the GRE based on the four common points recommended by Sivak and Flannagan (1993). The proposed beam pattern was a compromise between the North American and European philosophies (Sivak et al., 2000). Figure 7 shows the test points (top) and zones (bottom) above horizontal (note: while the proposed beam pattern includes points up to 90 degrees above horizontal, the figure stops at 12 degrees for simplicity) (GTB Coordinating Committee, 2002).

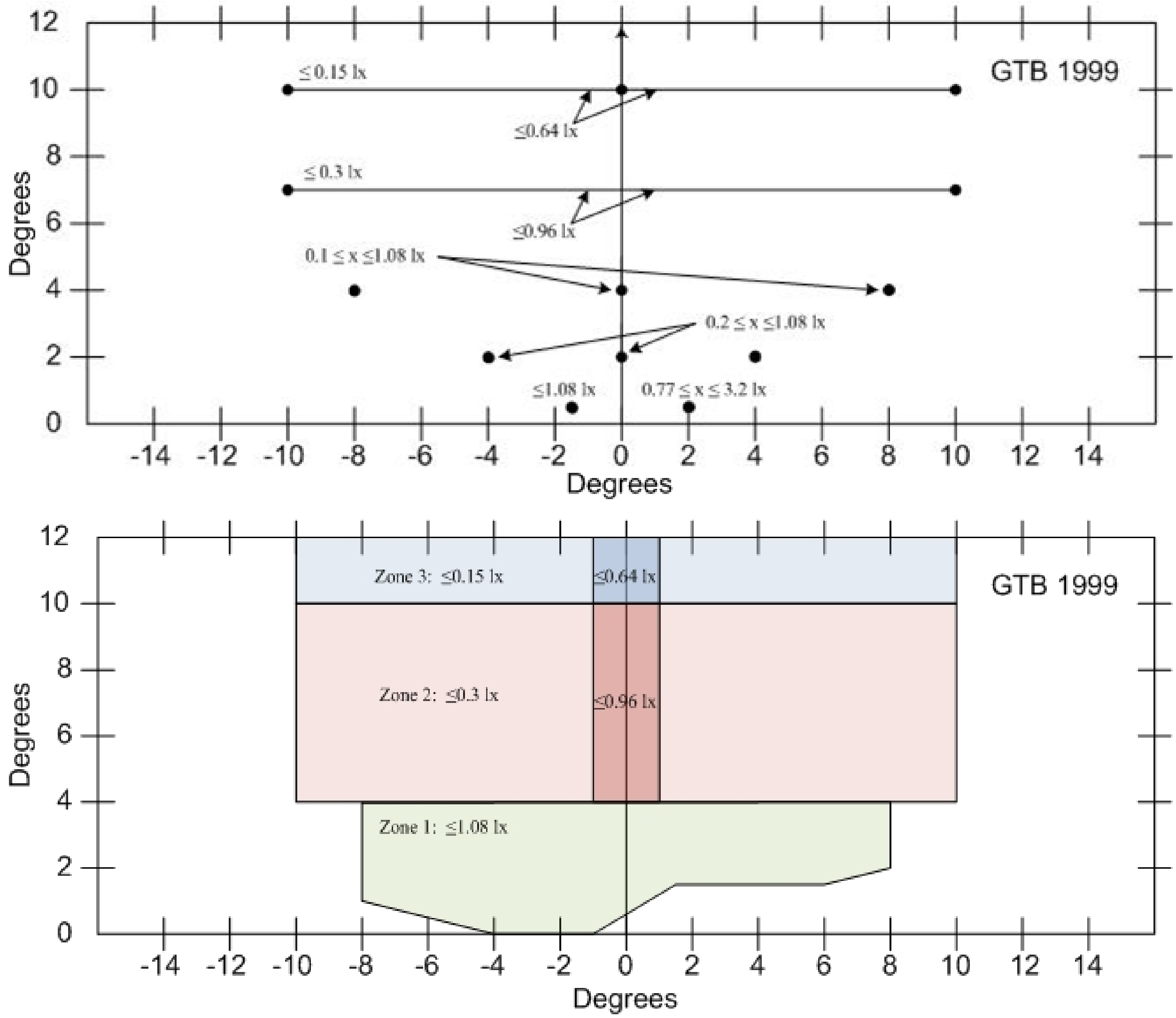


Figure 7. Test points (top) and zones (bottom) of the harmonized beam pattern proposed by the GTB.

In 2004, Schoettle, Sivak, Flannagan, and Kosmatka photometered 20 headlamps representing 39% of the headlamps on passenger vehicles being sold in the United States at that time, and determined the median luminous intensities. Of the median luminous intensity values at 1 degree up and from 0 to 5 degrees left, the average value was less than 500 cd. That is 28% less than the maximum allowed (700 cd) in FMVSS 108. Figure 8 shows the isocandela diagrams of the median luminous intensity for the sales-weighted sample.

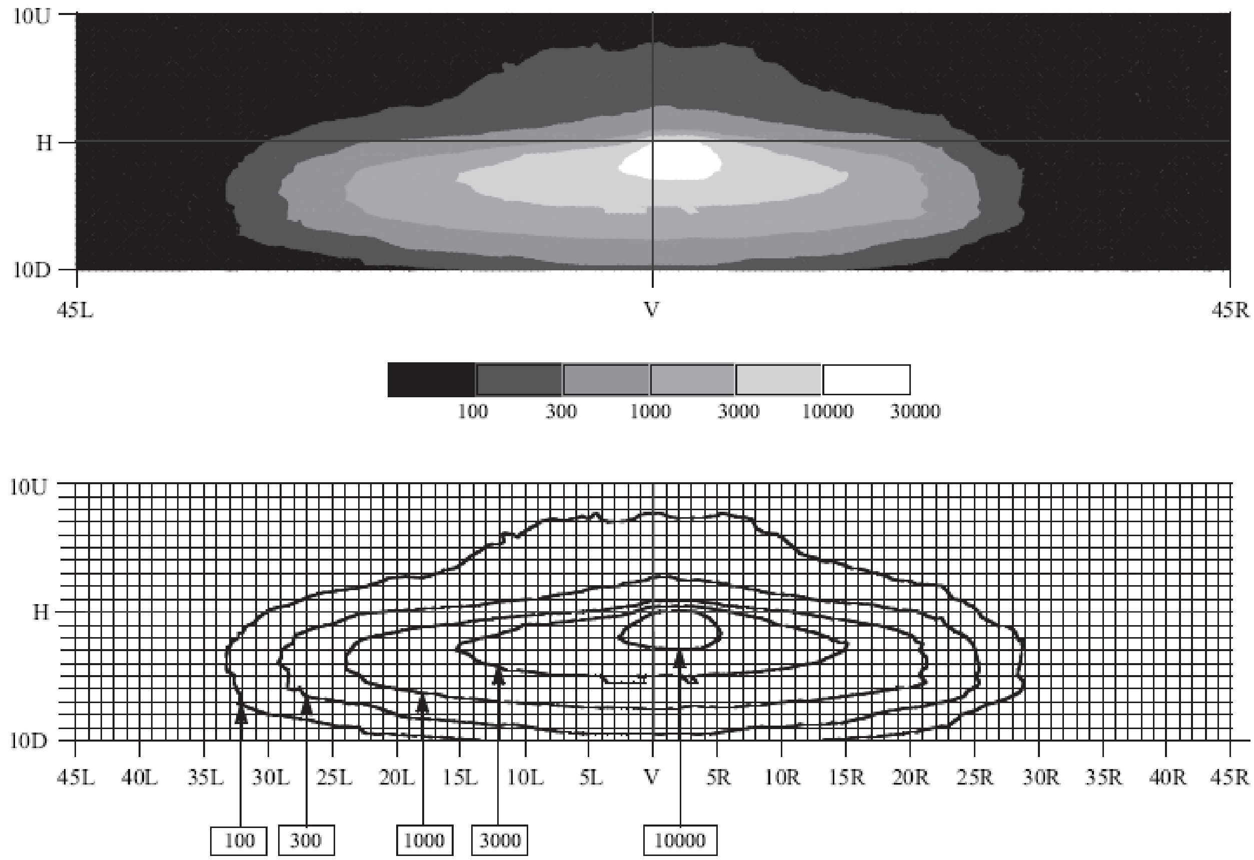


Figure 8. Isocandela diagrams of the median luminous intensities for sales-weighted sample representing the low-beam headlamps on current passenger vehicles in the U.S. The two panels represent the same information in two different formats. Maximum intensity: 22740 cd at 1.0°R, 1.0°D. (Test voltage:12.8V) (Source: Schoettle et al., 2004).

The efforts for a worldwide harmonized beam pattern with a focus on controlling glare for oncoming drivers has created a trend in U.S. headlamp standards for reduced light above the horizontal. The resulting beam patterns of today are much different than those when AASHTO was developing their design guidelines, and may not be well represented by them.

In addition to changes made to standards and regulations, the technology of headlamps has also evolved. Newer, brighter light sources, replaceable bulbs, and better reflectors and lenses have all contributed to the constant evolution of headlamps. Not only is the technology of modern headlamps different from the sealed-beam technology likely used in determining SD for sag vertical curves, but there are also many more varieties of headlamps, each with its own beam pattern.

COMPARISON TO STOPPING SIGHT DISTANCE

With the introduction of new light sources, the variety of headlamps has increased. Each light source has unique characteristics which have an impact on a driver's ability to see objects ahead. This is the critical detail for the sag vertical curves.

In 2005, the Federal Highway Administration (FHWA) published the Enhanced Night Visibility (ENV) study that investigated the performance of several types of headlamp configurations by determining the distance at which a driver could see an object in the road (Blanco, Hankey, and Dingus, 2005). Among the configurations tested were a standard halogen low beam (HLB), an HID low beam, and a low-profile halogen low beam (HLB-LP). By comparing the mean detection distance of an object (i.e., the distance at which a participant was able to see the object) with the calculated stopping distance, it was found that the stopping distance was compromised in several situations by the HLB and HID headlamps. Table 1, Table 2, and Table 3 below show the situations in which the stopping distance might be compromised for the HLB, HID, and HLB-LP, respectively.

Table 1. Detection Distance by Type of Object and Potential Detection Inadequacy when compared to Stopping Distance at Various Speeds: HLB

Type of Object	Det. (ft)	126 ft at 25 mi/h	197 ft at 35 mi/h	278 ft at 45 mi/h	370 ft at 55 mi/h	474 ft at 65 mi/h	529 ft at 70 mi/h
Tire Tread	240			X	X	X	X
Parallel Pedestrian, Black Clothing	386					X	X
Perpendicular Pedestrian, Black Clothing	409					X	X
Child's Bicycle	464					*	*
Cyclist, Black Clothing	566						
Perpendicular Pedestrian, White Clothing	828						
Parallel Pedestrian, White Clothing	839						
Static Pedestrian, White Clothing	858						
Cyclist, White Clothing	862						

X = stopping distance might be compromised; * = exceeds distance, but the scenario is not likely; 1 ft = 0.305 m; 1 mi = 1.6 km

Source: Blanco, Hankey, and Dingus, 2005

Table 2. Detection Distance by Type of Object and Potential Detection Inadequacy when compared to Stopping Distance at Various Speeds: HID

Type of Object	Det. (ft)	126 ft at 25 mi/h	197 ft at 35 mi/h	278 ft at 45 mi/h	370 ft at 55 mi/h	474 ft at 65 mi/h	529 ft at 70 mi/h
Tire Tread	212			X	X	X	X
Parallel Pedestrian, Black Clothing	275			X	X	X	X
Perpendicular Pedestrian, Black Clothing	282				X	X	X
Child's Bicycle	417					*	*
Cyclist, Black Clothing	444					X	X
Perpendicular Pedestrian, White Clothing	683						
Parallel Pedestrian, White Clothing	713						
Static Pedestrian, White Clothing	734						
Cyclist, White Clothing	796						

X = stopping distance might be compromised; * = exceeds distance, but the scenario is not likely; 1 ft = 0.305 m; 1 mi = 1.6 km

Source: Blanco, Hankey, and Dingus, 2005

Table 3. Detection Distance by Type of Object and Potential Detection Inadequacy when compared to Stopping Distance at Various Speeds: HLB-LP

Type of Object	Det. (ft)	126 ft at 25 mi/h	197 ft at 35 mi/h	278 ft at 45 mi/h	370 ft at 55 mi/h	474 ft at 65 mi/h	529 ft at 70 mi/h
Tire Tread	177		X	X	X	X	X
Parallel Pedestrian, Black Clothing	302				X	X	X
Perpendicular Pedestrian, Black Clothing	326				X	X	X
Child's Bicycle	399					*	*
Cyclist, Black Clothing	494						X
Perpendicular Pedestrian, White Clothing	721						
Parallel Pedestrian, White Clothing	744						
Static Pedestrian, White Clothing	778						
Cyclist, White Clothing	805						

X = stopping distance might be compromised; * = exceeds distance, but the scenario is not likely; 1 ft = 0.305 m; 1 mi = 1.6 km

Source: Blanco, Hankey, and Dingus, 2005

The ENV study (Blanco, Hankey, and Dingus, 2005) was conducted on the Virginia Smart Road, with objects presented on flat, straight portions of the road. The decreased SD in a sag vertical curve could cause a compromise of stopping distance in even more situations. This study highlighted how different headlight technologies can affect a driver's ability to see objects near the road and, therefore, the SSD.

In addition to the light source, headlamps must incorporate methods for distributing the light in the desired pattern. Early headlamps used lens optics. The light source was located at the focal point of a metallic parabolic reflector, which collected the light. As light bounced off of the reflector, and through the glass lens, optics molded into the lens would shift the light into the desired pattern. This was typical of most early sealed-beam headlamps (Moore, 1998).

In the 1980s, advancement in computer-aided drawing allowed the development of complex shape reflectors, which improved the efficiency of light collection and distribution. In the late 1980s, some U.S. vehicles used complex-reflector headlamps in conjunction with faceted optic lenses. The first multi-reflector headlamps to use a clear lens appeared on the 1990 Honda Accord, with the reflector designed for both light collection and distribution into the desired pattern. Today, modern reflectors are commonly made of plastic with a metallic coating.

Another method for collecting and distributing light from a source is projector optics. For this system, the light source is located at the focal point of an ellipsoidal reflector and a condenser lens is located at the front of the lamp. A shade located between the lens and the reflector is used to block a portion of the light to achieve the low or dipped-beam pattern. In some headlamps a separate lamp is used for high beams and, in others, the shade is removed from the path of the light.

Headlamps today come in many varieties. With several light sources with unique characteristics, several different methods of collecting and distributing light, and different—more regulated—beam patterns, it is easy to see why the equation for a sag vertical curve does not accurately represent modern headlamps with its assumed 1-degree uplight.

SUMMARY

Since the creation of sag vertical curve design guidelines, headlamps and their resulting beam patterns have changed significantly. The major driving forces behind this change are the introduction of newer technologies and an effort by industry groups to create a worldwide harmonized beam pattern.

Key changes in technology include the introduction of new light sources – most importantly, halogen and HID light sources – and new methods of collecting and distributing light. Today's clear-lens, complex-reflector, replaceable-bulb headlamps are a far cry from the traditional sealed-beam technology likely used in determining AASHTO's guidelines.

Key concerns in the regulation of headlamp beam patterns include forward visibility, proper illumination of roadway signs, and the reduction of glare for oncoming drivers. As industry groups attempt to harmonize the two major headlamp standards (SAE and ECE), the desire to decrease glare has taken a major role in the U.S. headlamp beam patterns' trend of decreasing and controlling the light above the horizontal. While more uplight is allowed to the right of vertical for the illumination of roadway signs and objects near the road, today's beam patterns are drastically different from those during the time of AASHTO's guidelines creation.

These factors underscore previous research which suggests that today's headlamps are not well represented in AASHTO's guidelines for the design of sag vertical curves, and why a closer look is needed to determine if changes need to be made to the guidelines.

CHAPTER 4 PRACTITIONER SURVEY RESULTS

As part of assessment of practice in the design of sag curves, a survey was administered to the highway agencies in every state and a review of practices by domestic and international agencies was conducted.

DOMESTIC STANDARDS

The survey was administered to the departments of transportation in all 50 states and Puerto Rico. The roster of the AASHTO (Highway) Subcommittee on Design as of December 2009 was used as the primary source for contacts.

Forty-two state DOT representatives responded to the survey (as indicated in Table 4). For the states that did not respond to the survey, the research team was able to gather information from the manuals for five of the states and no information was found for three of the states. Table 4 summarizes the findings.

The objective of the survey was threefold: first, to identify how many states have documented guidelines for sag vertical curve design; second, to identify which criteria were used (headlight SD, passenger comfort, drainage control, general appearance, SD at undercrossing, decision passing, SD considerations, and others); and third, to identify differences between these criteria and the ones in the AASHTO policy on Geometric Design of Highways and Streets (AASHTO, 2004). In addition, the survey helped to identify:

- design criteria on continuously lighted sections,
- any issues identified by the States that need to be addressed,
- any unpublished studies conducted by the States,
- the perception of safety on sag vertical curves, and
- if the state accident records identify accidents occurring on sag vertical curves.

The survey is shown in Appendix A. Most of the states responded to the questions by attaching a copy of the URL of their road design manual. The research team carefully examined all the state manuals to identify any deviations to the standard from the AASHTO policy and exemptions used in each jurisdiction. While this task was very time-consuming, it provided the research team with a great understanding of the states' policies and procedures. Any modification of the standard methodology was documented during the survey and a sample of these modifications is shown in this report.

Table 4. State Survey Responses

State	Documented Design Criteria		Criteria same as AASHTO		Situations where Different Recommendations are used		Criteria used when Designing Vertical Curves							Exemptions		Keep Accident Records		
	Yes	No	Yes	No	Yes	No	Headlight	Passenger Comfort	Drainage	Appearance	Undercrossing	Decision or Passing SD	Other	Yes	No	No	Yes	Not Sure
1		X	X				X						X	X			X	
2	X		X															
3	X		X			X	X		X	X		X	X	X			X	
4	X		X		X		X								X	X		
5	X			X		X	X	X					X		X	X		
6	X		X				X						X					
7	X		X			X	X	X			X			X		X		
8	X		X			X	X	X	X	X					X	X		
9	X		X		X		X	X	X	X	X			X				X
10	X		X			X	X		X		X	X		X		X		
11	X						X							X				
12	X		X			X	X		X					X		X		
13	X		X			X	X								X	X		
14	X		X		X		X	X	X	X	X	X			X	X		
15	X		X			X	X	X	X	X	X			X		X		
16	X		X		X		X	X	X	X			X	X		X		
17	X		X			X	X				X			X		X		
18	X			X	X		X	X	X	X	X	X	X	X				
19																		
20		X	X		X		X				X	X		X				X
21	X		X				X							X				X
22	X		X			X	X							X			X	
23	X		X				X	X		X			X					
24	X		X		X		X								X			X
25	X		X		X		X	X	X	X								
26	X						X		X	X				X		X		
27	X		X		X		X	X	X		X	X		X				

State	Documented Design Criteria		Criteria same as AASHTO		Situations where Different Recommendations are used		Criteria used when Designing Vertical Curves							Exemptions		Keep Accident Records		
	Yes	No	Yes	No	Yes	No	Headlight	Passenger Comfort	Drainage	Appearance	Undercrossing	Decision or Passing SD	Other	Yes	No	No	Yes	Not Sure
28	X		X		X		X								X	X		
29	X		X			X	X			X	X	X		X		X		
30	X		X			X	X							X			X	
31		X	X			X	X				X	X			X	X		
32	X		X		X		X	X	X	X	X			X		X		
33		X	X		X		X							X				X
34	X		X			X		X				X			X	X		
35	X		X		X		X			X					X	X		
36	X		X		X		X			X			X		X	X		
37	X		X			X	X								X	X		
38	X		X				X	X	X	X								
39	X		X		X		X	X	X	X	X	X		X		X		
40																		
41	X		X			X	X	X	X		X			X		X		
42	X		X			X	X	X	X	X		X		X		X		
43	X		X			X	X								X	X		
44	X		X			X	X						X	X				X
45	X		X			X	X	X	X	X	X	X	X	X			X	
46																		
47	X		X			X	X	X						X			X	
48	X		X			X	X	X							X		X	
49	X		X			X	X								X		X	
50	X		X			X	X	X	X	X	X	X		X				X
51																		

Note: The States are not shown in any particular order and for some cases information was completed by VTTI with available public information from online state information

Question 1

Does your Agency have documented design criteria for vertical sag curves (Road Design Manual, Design Specifications, etc.)?

Forty-three of the states which responded to this question have documented design criteria for vertical sag curves. Some of the states that do not have documented design criteria for vertical sag curves mentioned that they followed the AASHTO guide. All of the states use parabolic curves for the design of sag vertical curves.

Question 2

Are these criteria the same as the AASHTO "*AASHTO Policy on Geometric Design of Highways and Streets*"?

Most of the respondents (41) that do have documented design criteria indicated that their criteria are based on the AASHTO policy. The states that do not a have documented design criteria refer to the AASHTO policy as the design criteria used.

Only two states (California and Louisiana) answered that they do not follow the AASHTO guidelines. However, a close examination of their road design manuals shows only small differences or additional criteria. Similarly, while some states indicated that they followed the AASHTO policy, a detailed examination of their manuals found small differences.

In the case of the State of California, three differences are introduced:

1. Different computation of SSD,
2. Increase of SSD based on sustained downgrades, and
3. Minimum length of 10 V.

One of the major differences in design criteria in the California Design Manual is that the "Stopping sight distance is measured from the driver's eyes, which are assumed to be 3 ½-feet above the pavement surface, to an object ½-foot high on the road." In addition, "the SSDs in Table 5 should be increased by 20% on sustained downgrades steeper than 3% and longer than one mile." (Highway Design Manual, Chapter 200, Geometric Design and Structure Standards, Topic 201, pages 200-1 200-2, 2007).

Table 5. Stopping Sight Distance for California Department of Transportation (DOT) as compared with AASHTO

Design Speed	Stopping Sight Distance AASHTO	Stopping Sight Distance California
20	115	125
25	155	150
30	200	200
35	250	250
40	305	300
45	360	360
50	425	430
55	495	500
60	570	580
65	645	660
70	730	750
75	820	840
80	910	930

The formulas to calculate the length of the curve are the same as the ones in the AASHTO policy and the differences in SSDs resulted in small differences on the recommended k values (k = L/A ratio of curve length *L* to the algebraic difference in grade *A*) (Figure 9).

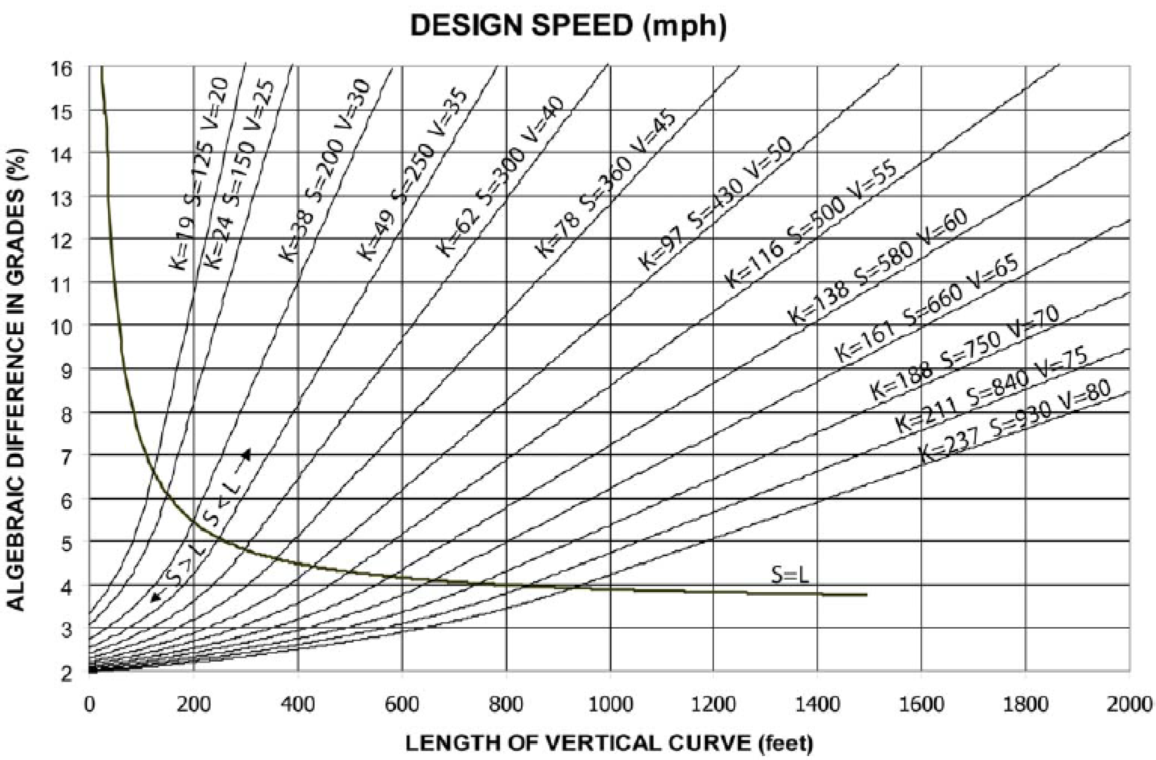


Figure 9. K values for California DOT. (Source: Highway Design Manual, Index 201/204, Geometric Design and Structure Design. California Department of Transportation, Jan. 2007)

The third difference is that:

"For algebraic grade differences of 2 percent and greater, and design speeds equal to or greater than 40 miles per hour, the minimum length of vertical curve in feet should be equal to 10V, where V = design speed. As an example, 65 miles per hour design speed would require a 650-foot minimum vertical curve length. For algebraic grade differences of less than 2 percent, or design speeds less than 40 miles per hour, the vertical curve length should be a minimum of 200 feet." (Highway Design Manual, Chapter 200, Geometric Design and Structure Standards Topic 204, page 200-18-19, 2007)

Louisiana DOT Design Standards recommend the minimum length of the vertical curve will be the longer of either 300 ft or that required by the formula LVC = KA, where K is the rate of vertical curvature and A is the algebraic difference in grades (in percent)(Roadway Design Procedures and Details, Chapter 4, Elements of Design, Cross Section Elements, page 4-7, Louisiana Department of Transportation and Development, January 2009)

North Dakota DOT is the only state DOT that uses passenger comfort as the primary criterion for sag vertical curves as shown in Table 6.

Table 6. Design Guidelines for New/Reconstruction Projects

Traffic Data	**Use 20 year projected**
Roadway Width	Use AASHTO Standards.
Superelevations	Use AASHTO Standards. (6% max superelevation, exhibit 3-22)
Design Speed	Use posted speed limit.
Cross Slope	Driving lanes 1.5 – 2.5%, Shoulder 6% max.
Horizontal Curvature	Use AASHTO Standards.
Vertical Curvature	**Interregional System:** Use stopping sight distance for crest curve design and **comfort curve design for sag curves**. Decision sight distance should be considered in areas where complex driver decisions are required such as intersections with major collectors or higher, interchanges, lane drops or additions, etc. Passing areas should be provided at reasonable intervals based on terrain and traffic volumes. A rule-of-thumb would be a passing area every 3 to 5 miles when the ADT <2000 and every 3 miles when the ADT >2000. **State Corridors, District Corridors & Collectors:** Use stopping sight distance for crest curve design and comfort curve design for sag curves. Passing areas should be provided at reasonable intervals based on terrain and traffic volumes. A rule-of-thumb would be a passing area every 3 to 5 miles when the ADT <2000 and every 3 miles when the ADT >2000.
Clear Zone	Use AASHTO roadside design clear zone.
Inslope	Use 4:1 except Interregional system > 2000 ADT and Interstate use 6:1.
Pavement Slough	Use AASHTO Standards.
Safety	Safety hardware to meet NCHRP 350 standards.

Source: Design Manual, Section I-06, Design Philosophy, North Dakota Department of Transportation, 2010, Page 11

Florida also modified the SSD, but only for Interstates, as is shown in the corresponding question 4.

Question 3

Are there any situations where your agency recommends the designer use different specifications than the ones specified in your answer for question 1?

Fifteen states pointed out that there are special situations where different specifications are recommended, and 26 states answered that they do not use a different specification. For the majority of the states the different specifications correspond to reconstruction and rehabilitation projects, the use of local City or County specifications, or – when appropriate – the use of AASHTO's Guidelines for Geometric Design of Very Low-Volume Local Roads.

In Arkansas, "[R]econstruction of vertical curves should be considered when the existing curve design, based on the stopping sight distance provided, correspond to a speed that is more than 20 mph below the average running speed established for the project, the traffic volume is more than 1,500 vehicles per day, and the curve hides a major hazard from view. If curve reconstruction is not justified, appropriate safety and other mitigation measures should be applied (Geometric Design Criteria for Non Freeway Resurfacing, Restoration and Rehabilitation Projects, page 10, Arkansas State Highway and Transportation Department Approved by FHWA 8/21/89."

In Florida, "[O]nly existing sag vertical curves where crash history (related to the curve) indicates a problem must be evaluated against new construction criteria. An evaluated sag vertical curve that does not meet the minimum K value requires a Design Exception to remain. Sag vertical curves that are to be reconstructed must meet new construction criteria. Sag vertical curves without crash problems that fall below new construction criteria do not require Design Exceptions or Design Variations to remain." (Plans Preparation Manual, Chapter 25, Florida's Design Criteria for Resurfacing, Restoration, Rehabilitation (RRR) of Streets and Highways, page 25-23, January 1, 2010)

In New York, sag vertical curve SD is not typically considered on Resurfacing Restoration and Rehabilitation (2R and 3R) projects: "Sag vertical curves need not be considered unless there are underpasses, overhead trees or there is an associated operational or safety problem." In North Carolina, in the case of 3R on two-lane roadways, "[A]n existing vertical curve may be retained if design speed is within 20 mph of the posted or statutory speed limit and the design volumes are less than 1,500 ADT. An existing vertical curve may be retained if the curve's design speed is within 10 mph of the posted or statutory speed limit and the crash rate is below the statewide average. A design exception is required for horizontal and vertical curves that do not meet the above RRR criteria." For four-lane roadways, "[A]n existing vertical or horizontal curve may be retained if the curve's design speed meets the posted or statutory speed limit. A design exception is required if the horizontal or vertical design speed is less than the posted or statutory speed."

In Utah, "Based on the stopping sight distance provided, an existing vertical curve may be retained as is without further evaluation if the existing curve design speed corresponds to a speed that is within 20 mph of the overall project design speed and the AADT [i.e., annual average daily traffic] is less than 1,500 VPD [Vehicles per day]. The reconstruction of a sag vertical curve is evaluated when:

1. The AADT exceeds 1,500 VPD.
2. The design speed based on SSD is more than 20 mph below the overall project design speed.
3. The vertical curve hides a major hazard such as intersections, sharp, horizontal curves or a narrow bridge.
4. The vertical curve is identified as a high accident location, above the statewide average."

The Roadway Design Manual of Mississippi DOT shows that different K values for 3R projects (as shown in **Table 7**) would be used.

Table 7. Minimum K Values for 3R and New Construction Projects for Sag Vertical Curves

V (mph)	SSD (f3et)	3R sag K value	New Construction sag K values
30	200	20	37
35	250	27	49
40	305	35	64
45	360	44	79
50	425	54	96
55	495	65	115
60	570	78	136
65	645	91	157
70	730	106	181

Source: Memorandum, Vertical Curve K-Values, Mississippi Department of Transportation, October 2008

Question 4

Which criteria do you use when designing Vertical Sag Curves?

When asked which criteria the state used when designing Vertical Sag Curves, the responses shown in Table 8 were obtained. Almost all states use headlight SD as the primary criteria. North Dakota is the only state that uses passenger comfort as the first criteria, and decision SD as the second criteria. The following section describes the criteria and the small differences with respect to the AASHTO guide.

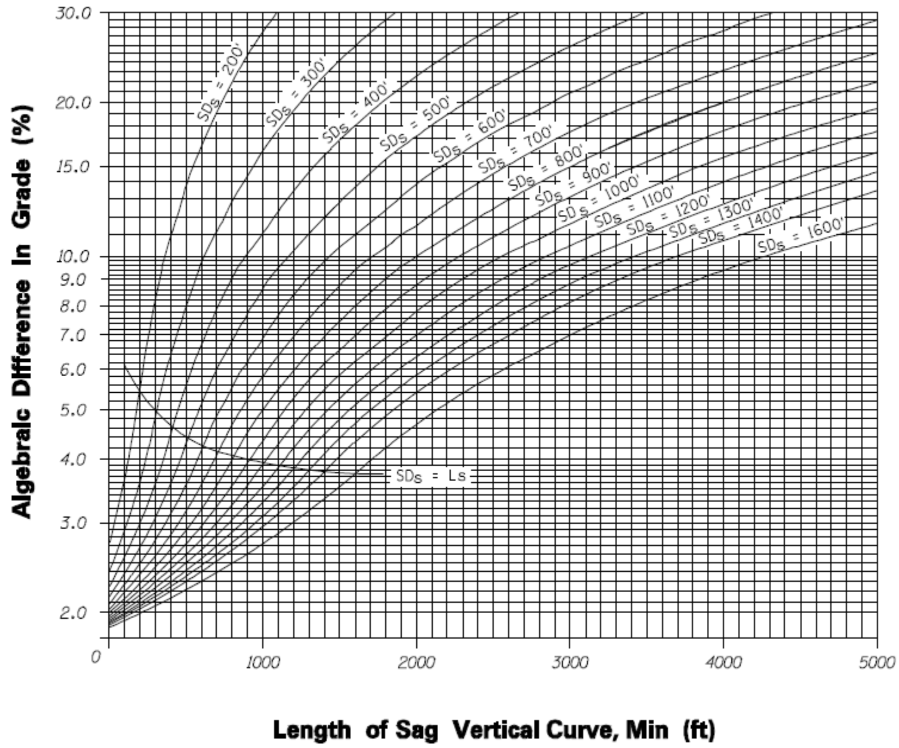
Table 8. Criteria used by the States for Vertical Sag Curve Design

Criteria	Number of Responses
Headlight SD	45
Passenger comfort	21
Drainage control	19
General Appearance	19
SD at Undercrossing	16
Decision or Passing SD considerations	13
Other	10

Headlight Sight Distance

All the states that used Headlight SD as a criterion specified that they used the AASHTO criteria of 2 ft for headlight height and a 1-degree upward divergence of the light beam from the longitudinal axis. Furthermore, following AASHTO guidelines that "…for overall safety on highways a sag vertical curve should be long enough that the light beam distance is nearly the same as the stopping sight distance" and because it is appropriate to use stopping SD for different design speeds as the light beam distance, most of the states specify the criteria directly as SSD and occasionally reference the headlight distance. On the same note, not all the states provided specifications when the SSD is more than the length of the curve. Some states incorporate additional modifications to the headlight SD; for example, Connecticut and California make a correction for grades and Florida changes the selected design speed for some specific types of highways. In addition, some states specify (as do some international standards) a lower and upper range of K based on assumed speed conditions.

Some states provide graphical representations that can slightly differ from AASHTO in the form of the curve, as is the case of Arizona (Figure 10).



For SDs < Lc $\quad Lc = \dfrac{A(SDs)^2}{400 + 3.5SDs}$

Where:
SD_S = Stopping Sight Distance, (ft)
Lc = Length of Sag Vertical Curve, Min (ft)
A = Algebraic Difference In Grade, (%)

For SDs > Lc $\quad Lc = 2(SDs) - \left(\dfrac{400 + 3.5SDs}{A}\right)$

Figure 10. Relation of minimum length of sag vertical curves to stopping sight distance (Source: Roadway Design Guidelines. Arizona Department of Transportation, 2007).

In other cases (e.g., Tennessee) the criteria for sag vertical curves are listed as a range as part of the series of drawings for each roadway typical section, as shown in Table 9.

Table 9. Design Standards – Freeway with Median Barrier

Design Standards (For given Design Speed)		Design Speeds (mph) 50	60	70
Minimum, I, Stopping Sight Distance (Feet)		400-475	525-650	625-850
Minimum K Values	Crest Vertical Curve	110-160	190-310	290-540
	Sag Vertical Curve	90-110	120-160	150-220
Maximum Grade	Level	4	3	3
	Rolling	5	4	4
	Mountainous	6	6	5

Source: Roadway Design Standards Section RD-TS, Tennessee Department of Transportation, March 2003

In Connecticut, whole headlight SD is the primary design control for sag vertical curves but the criteria also include minimum length grade adjustments. “When determining S for sag vertical curves, the designer should consider the effects of grade on stopping sight distance (SSD). The following thresholds may be used for determining the thresholds for ‘Level’ K values:

V > 50 mph: -1% < G < +1%
V < 50 mph: -2% < G < +2%
The selection of “G” at a crest vertical curve will depend on which grade is steeper and whether the roadway is one-way or two-way. On a one-way roadway, “G” should always be the grade on the far side of the crest when considering the direction of travel. On a two-way roadway, “G” should always be the steeper of the two grades on either side of the sag. Only the Level SSDs are applicable for design exemption purposes. For designs where because of rounding of the charts, the “level” SSD is met but not the k values, an exception will not be required.” (Connecticut Highway Design Manual Chapter Nine, Vertical Alignment, page 9(3)-6, December 2003, Survey) (**Table 10**).

Table 10. K Values for Sag Vertical Curves

Design Speed (mph)	Downgrades			Level	Upgrades		
	-9 %	-6 %	-3%	0%	+3 %	+6%	+9%
20	20	18	18	17	16	26	15
25	31	28	27	26	25	24	22
30	44	41	38	37	37	33	32
35	60	56	52	49	47	44	43
40	77	72	66	64	60	57	55
45	97	89	84	79	74	72	68
50	119	110	103	96	91	87	83
55	143	132	122	115	108	103	99
60	170	156	144	136	128	121	115
65	198	181	168	157	149	140	135
70	227	207	193	181	170	161	154

Source: Connecticut Highway Design Manual, Chapter 9, Vertical Curves, Connecticut Department of Transportation, December 2003

In Colorado "Vertical curves are not required where algebraic grade difference is less than 0.20 percent. In rural applications, the minimum length of vertical curves on main roadways, both crest and sag, should be 300 feet. For other applications, the minimum length should be about three times the design speed". (CDOT Roadway Design Guide, Chapter 3, Elements of Design, page 3-35).

For Florida, the stopping sight distance and the corresponding k values for the Interstate Highways are computed based on design speeds of 5 mph higher than the design speed of the Interstate. Florida has specific minimum sag vertical curve lengths for Interstates and high-speed arterials and collectors (>45 mph) that exceed the AASHTO minimum length." *Plans Preparation Manual, Chapter 2, Design Geometrics and Criteria, Florida Department of Transportation, January 2010.*

The Kansas Design Manual states that "…the minimum length of sag vertical curves is based on SSD, except for appearance considerations, where practicable use a minimum length of sag vertical curve of 300 feet." (Kansas Design Manual, Volume I Part A&B, Section 7.7.33, pages 7-67, November 2008 Edition.)

New Hampshire specified lower and upper ranges for sag vertical curves based on the assumed speed for condition, as shown in Table 11.

Table 11. Design Control for Sag Vertical Curves' Upper and Lower Ranges

DESIGN CONTROL FOR VERTICAL SAG CURVES BASED ON STOPPING SIGHT DISTANCE					
Design Speed	**Assumed Speed for Condition**	**Coefficient of Friction**	**Stopping Sight Distance For Design**	**Rate of Vertical Curve K**	
(km/h)	(km/h)	F	(m)	Computed	Rounded by Design
30	30-30	0.40	29.6-29.6	3.88-3.88	4-4
40	40-40	0.38	44.4-44.4	7.11-7.11	8-8
50	47-50	0.35	57.4-62.8	10.20-11.54	11-12
60	55-60	0.33	74.3-84.6	14.45-17.12	15-18
70	63-70	0.32	94.1-110.8	19.62-24-08	20-25
80	70-80	0.30	112.8-139.4	24.62-31.86	25-32
90	77-90	0.30	131.2-168.7	29.62-39.95	30-40
100	85-100	0.29	157.0-205.0	36.71-50.06	37-51
110	91-110	0.28	179-5-246.4	42.95-61.8	43-62
120	98-120	0.28	202.9-285.6	49.47-72.72	50-73

Source: New Hampshire Design Manual, 4-35

Nebraska uses the same values from AASHTO for the Minimum SSD but specified that "…these values do not meet intersection SD requirements and all intersections and driveways, except for field entrances, shall be evaluated for intersection SD" (Nebraska Department of Roads, Roadway Design Manual, Chapter 3: Roadway Alignment, page 3-34, July 2006), as shown in Figure 11.

U.S. Customary								
Sag Vertical Curve								
Design Speed (mph)	Minimum Stopping Sight Distance ①		Desirable Stopping Sight Distance (2-Lane, Left-Turn Condition and 2-Lane w/TWTL** , Left-Turn Condition) ②		Desirable Stopping Sight Distance (5-Lane and 4-Lane Divided w/16' Median, Left-Turn Condition) ③		Desirable Stopping Sight Distance (4-Lane Divided w/40' Median, Left-Turn Condition) ④	
	Length (ft)	Rate of Vertical Curvature K*	Length (ft)	Rate of Vertical Curvature K*	Length (ft)	Rate of Vertical Curvature K*	Length (ft)	Rate of Vertical Curvature K*
35	250	49	453	103	494	115	540	127
40	305	64	517	121	564	134	617	149
45	360	79	582	139	635	154	695	170
50	425	96	647	157	706	174	772	192
55	495	115	711	175	776	193	849	214
60	570	136	776	193	847	213	926	236
65	645	157	841	212	917	233	1003	257
70	730	181	906	230	988	253	1080	279

Figure 11. Design control for sag vertical curves (Source: Nebraska Department of Roads Roadway Design Manual page 3-34).

The Illinois DOT considers grade adjustment when the sag curve is between two downgrades and the downgrades are -3 percent or greater   However, grade adjustment K values do not require a design exception when not met, as shown in Figure 12.

K VALUES ROUNDED FOR DESIGN								
US Customary								
Design Speed (mph)	(3%)	(4%)	(5%)	(6%)	(7%)	(8%)	(9%)	(10%)
30	38	39	41	41	42	43	44	46
35	52	53	55	56	57	59	60	61
40	67	69	71	72	73	76	77	80
45	84	85	88	89	92	95	98	100
50	103	104	107	110	113	115	120	124
55	122	125	129	132	136	139	143	147
60	144	149	151	156	160	164	170	174
65	168	172	177	181	186	191	198	203
70	193	198	203	208	215	220	227	234

Figure 12. K values for sag vertical curves stopping sight distances for passenger cars, adjusted for downgrades (Source: Bureau of Design & Environment Manual, Ch. 33, Vertical Alignment, Illinois Department of Transportation, December 2002, Page 33-4f).

Passenger Comfort

Passenger comfort was specified as a criterion by 21 states. For most of the states, SSD or headlight SD is the primary control, with the exception of the North Dakota DOT that uses passenger comfort as the primary criterion for sag vertical curves and passing SD in special situations,

In general, the states check for the AASHTO comfort criteria based on the assumption that riding on a sag vertical curve is comfortable when centripetal acceleration does not exceed 0.3 m/s2. The standards are shown as a graph or table, such as Minnesota's standards are shown in Figure 13.

L = MIN. LENGTH OF VERTICAL CURVE, FT.
A = ALGEBRAIC DIFFERENCE IN GRADES, %
K = RATE OF VERTICAL CURVATURE PER CHANGE IN GRADE

USE COMFORT SAG VERTICAL CURVE EQUATION

$$L = \frac{AV^2}{46.5} = KA$$

DESIGN CONTROLS
FOR COMFORT SAG VERTICAL CURVES

K	DESIGN SPEED (m.p.h.)	DEGREE OF CURVE (minimum)
19	30	30° 09'
34	40	16° 51'
54	50	10° 37'
77	60	7° 26'
105	70	5° 27'

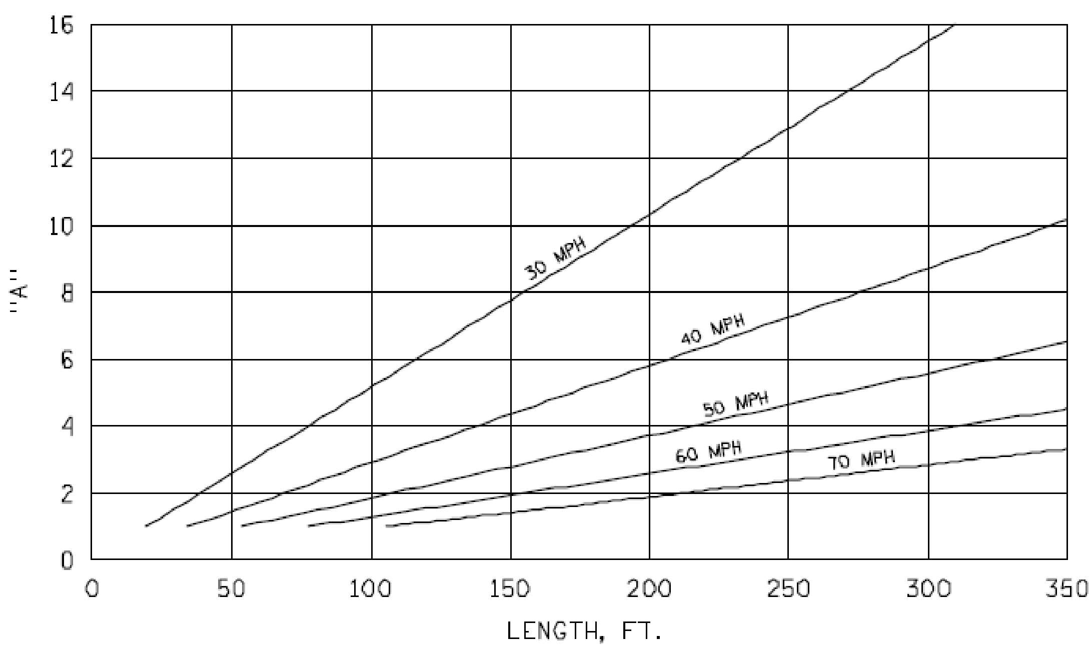


Figure 13. Design controls for comfort sag vertical curves. (Source: Road Design Manual, Chapter 3-4, Vertical Alignment, Minnesota Department of Transportation, 2004, Page 3-4(12)).

Texas standards acknowledge that passenger comfort is one of the criteria recognized to some extent to define sag vertical curves, but the standards specify that:

"Because cost and energy conservation considerations are factors in operating continuous lighting systems, headlight sight distance should be generally used in the design of sag vertical curves. Comfort control criteria are about 50 percent of the sag vertical curve lengths required by headlight distance and should be reserved for special use. Instances where the comfort control criteria may be appropriately used include ramp profiles where safety lighting is provided and for economical reasons in cases where an existing element, such as a structure not ready for replacement, controls the vertical profile. Comfort control criteria should be used sparingly on continuously lighted facilities since local, outside agencies often maintain and operate these systems and operations could be curtailed in the event of energy shortages." (Roadway Design Manual, Section 5 Vertical Alignment, page 7, Texas DOT 05/01/10)

Drainage Control

Drainage is used as a control criterion after checking for SSD by 19 states. Most of the states use the same AASHTO criteria whereas drainage problems should not be experienced if the vertical curvature with a minimum longitudinal grade of at least 0.3 percent is reached at a point about 50 ft of the level point. This criterion corresponds to K of 51 m or 167 ft. However, some states have slightly modified criteria, as described below.

For Arizona, the desirable minimum grade for a highway with a curb and gutter section is 0.4%. Special care should be taken in checking storm water drainage requirements to keep the spread of water on the travel way within tolerable limits. Above a 4,000-ft elevation, the minimum grade for roadways with curb and gutter shall be 0.5 percent (Roadway Design Guidelines, section 204.3 page 200-26, ADOT).

According to Indiana DOT, drainage problems are minimize, if a minimum longitudinal gradient of at least 0.3 percent is reached at a point about 50 ft from either side of the low point (that corresponds to a K value of 167 or less) and there is at least at least 0.25 feet elevation differential between the low point in the sag and the two points 50 ft to either side of the low point. If this K value is exceeded, it may be necessary to install flanking inlets on either side of the low point (Indiana Design Manual Section 44-3.02 (03), 2010).

General Appearance

General Appearance was selected as a criterion by 19 states. When appearance was included as one of the criteria, most of the time it is in the form of a required minimum length and occasionally as a specific issue (such as broken back curves).

Appearance concerns were an issue for broken back curves for Arizona (Roadway Design Guidelines, section 204.4, page 200-27, ADOT): "[B]roken back vertical curves consist of two vertical curves in the same direction separated by a short tangent grade section. Profile grade lines with broken back curves should be avoided, particularly in sag vertical curves where the unpleasing alignment is in full view."

The Indiana Design Manual states that the minimum length of a sag vertical curve in feet should be 3.2 V (which is slightly longer than the AASHTO criteria). This condition can be avoided if the existing conditions make it impractical to use the minimum length criteria. One exception may be applied in a curved section and is as follows: "if the sag is in a "sump," the use of the minimum length criteria may produce longitudinal slopes too flat to drain the storm water without exceeding the criteria for the limits of ponding on the travel lane.' (Indiana Design Manual Section 44-3.02, Item 3, 2010.)

The Oklahoma DOT differs from the AASHTO specification that the minimum length of a sag vertical curve should be 3V when the sag "is in a "sump." The use of the minimum length criteria may produce longitudinal slopes too flat to drain the storrmwater without exceeding the criteria for the limits of ponding on the travel lane (Design Manual Section 7, Vertical Alignment, Oklahoma Department of Transportation July 1992, page 7.2 (11)).

For Montana, the minimum length of a curve is Lmin = 3V and for aesthetics, the suggested minimum length of a sag vertical curve on a rural highway is 1,000 ft (300 m). Also, "sharp horizontal curves should not be introduced at or near the low point of pronounced sag vertical curves or at the bottom of steep vertical grades. Because visibility to the road ahead is foreshortened, only flat horizontal curvature will avoid an undesirable, distorted appearance". (Road Design Manual, Ch 10, Vertical Alignment, Montana Department of Transportation, 10.2 (2) April 2006)

New Hampshire DOT established minimum lengths of vertical curves based on design speeds, as shown in Table 12.

Table 12. Minimum Vertical Curve Lengths

Design Speed (km/h)	Length (m)
50	30
60	50
80	70
100	80
110	100

Source: Highway Design Manual Chapter 4, Alignment and Typical Section, New Hampshire Department of Transportation, March 1999

Decision Sight Distance

Decision SD was selected as a criterion by 13 states. However, for some states that mentioned this as a criterion, a detailed revision of the manual did not show any specification of decision SD for sag vertical curves. The decision SD is usually checked as a secondary criterion where there are complex decisions involved, as in the cases specified by North Dakota and Indiana and Illinois

North Dakota has different rules of thumbs for passing SD depending on the type of project. The following applies to New/Reconstruction projects:

"Interregional System: Decision sight distance should be considered in areas where complex driver decisions are required, such as intersections with major collectors or higher, interchanges, lane drops or additions, etc. Passing areas should be provided at reasonable intervals based on terrain and traffic volumes. A rule-of-thumb would be a passing area every 3 to 5 miles when the ADT <2000 and every 3 miles when the ADT >2000.
State Corridors, District Corridors & Collectors: Passing areas should be provided at reasonable intervals based on terrain and traffic volumes. A rule-of-thumb would be a passing area every 3 to 5 miles when the ADT <2000 and every 3 miles when the ADT >2000." (North Dakota Design Manual, Section I-06.03, revised 2/4/10.)

According to the Illinois DOT, *sight distance* may be warranted *at some locations*. *Figure 14* shows the K values for the decision SD for specific candidates' situations.

US Customary										
Design Speed (mph)	Avoidance Maneuver A (Stop on Rural Road)		Avoidance Maneuver B (Stop on Urban Road)		Avoidance Maneuver C (Speed/Path/Direction Change on Rural Road)		Avoidance Maneuver D (Speed/Path/Direction Change on Suburban Road)		Avoidance Maneuver E (Speed/Path/Direction Change of Urban Road)	
	DSD (ft)	K-Value	DSD (ft)	K-Value	DSD (ft)	K-Value	DSD (ft)	K-Value	DSD (ft)	K-Value
30	220	23	490	112	450	94	535	133	620	179
35	275	35	590	162	525	128	625	181	720	241
40	330	51	690	221	600	167	715	237	825	316
45	395	73	800	297	675	211	800	297	930	401
50	465	101	910	384	750	261	890	367	1030	492
55	535	133	1030	492	865	347	980	445	1135	597
60	610	173	1150	613	990	455	1125	587	1280	760
65	695	224	1275	754	1050	511	1220	690	1365	864
70	780	282	1410	922	1105	566	1275	754	1445	968
Metric										
(km/h)	DSD (m)	K-Value	DSD (m)	K-Value	DSD (m)	K-Value	DSD (m)	K-Value	DSD (m)	K-Value
50	70	8	155	37	145	32	170	44	195	58
60	95	14	195	58	170	44	205	64	235	84
70	115	21	235	84	200	61	235	84	275	115
80	140	30	280	120	230	81	270	111	315	151
90	170	44	325	161	270	111	315	151	360	197
100	200	61	370	209	315	151	355	192	400	244
110	235	84	420	269	330	166	380	220	430	281

Notes:

1. *See Section 31-3.02 for decision sight distances (DSD).*
2. $K = \frac{DSD^2}{2158}$, *where:* $h_1 = 3.5$ ft, $h_2 = 2$ ft *(US Customary)*
3. $K = \frac{DSD^2}{658}$, *where:* $h_1 = 1.080$ m, $h_2 = 600$ mm *(Metric)*

Figure 14. Decision sight distance for sag vertical curves — passenger cars (Source: Bureau of Design & Environment Manual, Ch. 33, Vertical Alignment, Illinois Department of Transportation, December 2002, 33-4 G).

Other

Other was selected as a criterion by 10 states. Most of the criteria qualified under *Other* involved a minimum curve length (such as in Alabama, Arizona, and Connecticut), or special erosion considerations (in Florida).

Alabama requires a minimum curve length of 800 ft for arterials and 1000 ft for freeways.

In Arizona, sag vertical curve not only shall be long enough that the light beam distance is nearly the same as the SSD, but the SD requirements for vertical curves also needs to satisfy minimum length requirements, as shown in Table 13.

Table 13. Relation of Highway Types to Vertical Curves' Minimum Length

Highway Types	Min Length (ft)
Controlled Access Highways	
Rural Areas	1000
Urban Areas	800
Rural Highways	800
Urban Highways	Three times design speed

Source: Roadway Design Guidelines, Arizona Department of Transportation. Jan 02, 2007

On certain occasions, due to critical clearance or other controls, the use of asymmetrical curves may be required. In the case of the South Dakota Road Design Manual, (pages 6-15), "The K value for unsymmetrical curves can be computed by using the reciprocal of the following formulas:

$$r1 = \frac{(g2 - g1)}{L} * \frac{I2}{I1}$$

$$r2 = \frac{(g2 - g1)}{L} * \frac{I1}{I2}$$

Therefore K = 1/r1 and K = 1/r2."

Florida requires paving of 4 ft of the median shoulder for 100 ft to either side of a sag vertical curve low point on divided arterials and collectors. In addition, the state has specifications for shoulder and slope treatment in sag vertical curves for protection from concentrated roadway runoff erosion and shoulder raveling.

Question 8

Does your Agency have any specifications for the case of sag vertical curves underpassing a structure?

Sixteen of the states mentioned that they had specifications for the case of vertical sag curves underpassing a structure. However, some states (such as Virginia) mentioned that they followed the AASHTO standard. In any case, the criterion is to check the sag vertical curves to ensure that the underpass structure does not obstruct the driver's visibility. Illinois DOT modified the AASHTO formula

Question 9

What are the design criteria for vertical sag curves in the case of Continuously Lighted Sections of highway?

Most of the states do not have specific design criteria for continuously lighted sections, but lighting can be considered as a mitigation factor in several states, as shown in Table 14.

Table 14. Standards or Current Practices for Continuously Lighted Sections (Based on Survey Responses)

Standard
Same as unlighted
Departmental policy on illumination does not make reference to vertical curvature. Primary design guide is AASHTO's Roadway Lighting Design Guide.
Stopping Sight distance
No, but is considered for cases where headlight sight distance is not met
There are no special standards. An exception to standards is required when sight distance is only obtained through illumination
Not available
Same criteria as in unlighted sections
Lighting is a mitigation strategy for substandard vertical alignment. GDOT refers to the FHWA publication, "Mitigation Strategies for Design Exceptions."
Same criteria as in unlighted sections
Comfort
Except in the design of underpass grades, sag vertical curves may meet comfort criteria where necessary
Prefer the use of headlight criteria, but comfort criteria may be acceptable upon review.
No special considerations are provided in our design manual
KYTC does not consider continuously lighted sections when designing vertical sag curves.
The same as those from AASHTO
We use the same design criteria for the sag curve regardless of lighting.
No difference
For $S < L$, lighted sag curve is a mitigation factor when stopping sight distance (K) is not met.
On lighted urban streets, comfort criteria may be used.
No
We always meet the AASHTO design criteria if we can. If we can't and we have overhead lighting, we will get a design exception
Not available
None
The same design controls are used for lighted sections of highways. Maintenance for lighting can be funding issue.
Passenger comfort and decision sight distance in areas where complex driver decisions are required
Same as the unlighted. However, the lighting can be used for mitigation of sag curves requiring design exception
Same criteria as in unlighted sections

A "comfort" sag may be used with a design exception approved by the State Roadway Engineer
None
In cases of fully lighted sections of highway, the sag vertical curve may be designed to meet the comfort criteria.
Design criteria for vertical sag curves in lighted sections of highway are the same as for sections of highway that are not lighted
50% of the sag vertical curve lengths
When K values at or near the lower end of the design range are used, they consider providing fixed street lighting with the UDOT Traffic and Safety Division.
NO change in criteria for lighted sections. However if the K value is not met, then a Design Exception is required. Mitigation for not meeting the appropriate K value is the fact that lighting is provided through the sag and they do allow the curve to be designed based on comfort No change in criteria for lighted sections.

Question 10

Does your agency allow short vertical sag curves in special situations (economic reasons, ramps, etc.)?

Some states allow short vertical curves in special situations. The following are examples of such cases.

The Alaska Highway Preconstruction Manual states that “an analytical method is not available to analyze accidents at sag vertical curves. Generally, sag vertical curves that do not meet AASHTO requirements may remain. If a grouping of accidents at a sag vertical curve appears to be an anomaly when compared to similar curves, an improvement may be needed if cost-effective.” *Alaska Preconstruction Manual, Section 1160, Page 1160-14, Roadside Geometry. Alaska Dept. of Transportation. Jan. 01, 2005*

In Arizona, the ADOT’s desirable minimum length for vertical curves (800 ft or 1000 ft) can be waived if necessary to meet existing constraints, and the state makes exception for driveways and ramp vertical curves:

> Urban driveways: The driveway grade, up or down, should be not be greater than six percent beginning at the outer edge of sidewalk. Desirably, the driveway grade adjacent to the sidewalk should be between plus or minus two percent for a distance of 10 ft minimum for residential driveways and at least 20 ft but preferably greater than 40 ft for commercial and industrial driveways. Grade breaks greater than six percent require vertical curves at least 10 ft long. In setting the driveway grade, consideration should be given to the impact of roadway drainage on the adjacent property. (Arizona Roadway Design Guidelines, Section 404.3, pages 400-12.)
>
> Ramp vertical curves: Interchange ramp vertical curves should be a minimum of 200 ft in length at the terminus with a crossroad. Elsewhere, the ramp vertical curve lengths should be in accordance with the ramp design speed with a minimum length of 400 ft. (Arizona, Roadway Design Guidelines, Section 540.1, pages 500-100.)

The New Hampshire DOT "…endorses minimum desirable lengths of vertical curves, although shorter ones will comply with the "Green Book" criteria." (Highway Design Manual Chapter 4, alignment and typical section, pages 4-38 New Hampshire DOT, March 1999.)

The Utah Roadway Design Manual of Instruction states that sag vertical curves may have a length less than that required for SSD when all three of the following are provided:

1. An evaluation upgrade to justify the length reduction.
2. Continuous illumination.
3. Design for the comfort of the vehicle occupants. The sag vertical curve lengths designed for comfort are about 50 percent of those required for SD.

Occasionally, the sag vertical curve can be avoided when certain conditions are met. For example, the Texas DOT states, "…designing a sag or crest vertical point of intersection without a vertical curve is generally acceptable where the grade difference (A) is:

1.0 percent or less for design speeds equal to or less than 45 mph [70 km/h]
0.5 percent or less for design speeds greater than 45 mph [70 km/h].

When a grade change without vertical curve is specified, the construction process typically results in a short vertical curve being built (i.e., the actual point of intersection is "smoothed" in the field). Conditions where grade changes without vertical curves are not recommended include: bridges (including bridge ends), direct-traffic culverts, and other locations requiring carefully detailed grades." (*Roadway Design Manual, Section 5 Vertical Alignment, page 8, Texas DOT 05/01/10)*

In addition the following answers were received in response to this question

"…long vertical curves on urban streets are generally impractical. The designer will typically need to lay out the profile grade line to meet existing conditions. Therefore, no minimum vertical curve lengths are provided for urban streets. Where practical, VPI's should be located at or near the centerlines of cross streets. Vertical curves will not be required when the algebraic difference in grades is less than 1.0 percent. However, the use of vertical curves should be evaluated when the algebraic difference in grades is greater than 0.5 percent. In addition, at signalized and stopped controlled intersections, some flattening of the approaches may be required."

"We allow shorter vertical sag curves at some sites where bridges are being replaced and on detours"

"Exceptions are granted for low speed/low-volume roadways, in the name of practical solutions."

"when the required K value does not meet design speed, then a shorter length of VC is allowed as long as the graphically plotted curve provides measured SSD through the curve in feet meets the design speed."

"If the cost of bringing the vertical curve up to the standard exceeds the benefit, the department has a process to provide justification of nonstandard and nonconforming features. This justification includes the computation of advisory speed, accident analysis, cost estimates, and mitigation factors."

Question 11
Has your agency identified any issues with the current design criteria for vertical sag curve that need to be addressed?

The following answers were received in response to this question:
"We question the real need for this to be one of the 13 AASHTO Controlling Criteria or at least question its relative importance. If the criteria is really only based on nighttime lighting, how important is it? Lots of things are hard to see at night and other criteria are based on daylight driving. We believe the criteria should be relaxed, eliminated, or considered differently."

"*We think that the criteria may need to be updated as your email suggests. We think that with the technological improvements to modern vehicles that headlight sight distance may not be as critical to safety as the current values suggest."*

"No, although it is felt that meeting design speeds for sag vertical curves is less critical than for crest vertical curve."

"In some cases, the K value is not met for the sag curve, however the required stopping sight distance is actually available for the curve (determined by plotting the curve information and measuring the SSD with a ruler). This has been the case for extremely short sag vertical curves with small algebraic differences between the two grades."

"Green book criteria are applied; however we recognize that headlight considerations will not be a control."

Other

All the states responded that they have not conducted any study regarding design or safety of vertical design curves.

Twenty-five states did not identify using their accident records if accidents occurred in a sag vertical curve. Seven states (Alabama, Arizona, Michigan, Utah, Virginia, West Virginia, and Washington) identified accident records occurring in sag vertical curves.

INTERNATIONAL STANDARDS

In addition to the domestic survey, an international literature search was undertaken to consider alternatives to the U.S. methodologies. Criteria and K values for several countries were obtained with different degrees of detail, depending on information availability; the countries include Canada, England, New Zealand, Spain, and Sweden. There are some major differences between U.S. standards and those of some European countries; one being the use of circular curves in some of the European countries instead of parabolic vertical curves which are used in the United States. For this case the K values represent the radius of the vertical curve. In reality, for a given K value, the differences between the alignment of the parabolic and circular curves represent only a few centimeters. In addition, for some countries, headlight SD is the dominant criteria while, for others, comfort or appearance is more prevalent. In some cases (for example, New Zealand), headlight SD is also limited. Maximum rates of vertical acceleration vary from 0.3m/s2 to 0.05g to 0.1 g. Exceptions from the absolute minimum are permitted and are computed as using Design Speed Steps (Ireland) or minimum and desirable K values (Spain). Australia's approach was to modify the graphics for minimum size sag vertical curves and aesthetics governed for highways and high-speed freeways. In England, adequate riding comfort is the major criterion for speeds higher than 70 mph. Australia just modified the new guide and, depending on the category of road, the governing criteria as well. The following section describes the minimum K values and criteria for different countries.

New Zealand

The *Transit New Zealand State Highway Geometric Design Manual* (Section 5 Vertical Alignment; Transit New Zealand, 2002) states that vertical curves are defined by two parameters:

- A comfort factor which provides for a smooth passage from one grade to another, and
- A safety factor which ensures that drivers have a safe SD over the full length of the vertical curve.

The profile must ensure that all relevant design speed SD requirements are met at every point on the road alignment. It is also good design practice to make the vertical alignment design speed 10 to 15 km/h greater than the horizontal alignment design speed, to provide an additional safety margin.

Visibility and comfort are the most important factors in vertical curve design. Sag vertical curves ***must*** ensure vehicle occupant comfort (i.e., the rate of vertical acceleration), and headlight performance criteria ***must*** be met. Other factors which must also be considered in sag vertical curve design are drainage requirements and sight line restrictions caused by overhead structures.

Appearance Requirements

"For very small changes of grade, vertical curves have little effect on the appearance of the road's profile and may usually be omitted. Short vertical curves can, however, have a significant effect on the appearance of a road's profile; therefore, <u>vertical curves for small changes of grade should have K values significantly greater than those needed for minimum sight distance reasons</u>. This is particularly important on high standard roads, especially for sag curves." (Transit New Zealand, 2002, pages 5-6.)

Table 15 shows the minimum length of vertical curve for satisfactory appearance. Longer curves are preferred when they can be achieved without conflict with other design requirements (such as drainage).

Table 15. Vertical Curve Appearance Criteria

Design Speed (km/h)	Maximum Change of Grade without a Vertical Curve (9%)	Minimum Length of Vertical Curve for Satisfactory Appearance (m)
40	1.0	20-30
60	0.8	40-50
80	0.5	60-80
100	0.4	80-100
120	0.2	100-150

Source: Transit New Zealand, 2002

According to the Manual, during nighttime the vehicle headlight performance limits the effective SD to between 120 and 150 m on unlit roads that is suitable only for speeds up to 90 km/h, so on dual-carriageway state highways a headlight SD of 150 m must be provided for sag vertical curves (Figure 15).

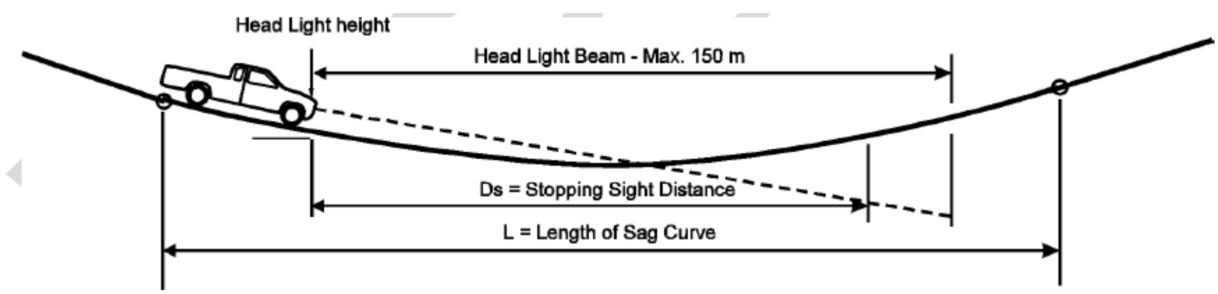


Figure 15. Sight line distance.

When sag vertical curves cannot be flattened to provide headlight stopping distance, they must provide an adequate level of ride comfort.

Comfort Requirements

Regarding Comfort Requirements the Geometric Design Manual states “For normal road design purposes, the vertical acceleration generated when passing from one the grade to another is limited to a maximum of 0.05*g*, where *g* is the acceleration due to gravity (9.8 m/sec2). On low standard roads and at intersections, a vertical acceleration of 0.10*g* may also be used where necessary. The vertical component of acceleration normal to the curve when traversing the path of a parabolic vertical curve at uniform speed is given by”:

$$a = \frac{V^2}{12960\ K}$$

Where:
a = vertical component of radial acceleration (m/sec2)
V = speed (km/h)
K = a measure of vertical curvature (m / 1% change of grade)

Sight Distance Requirements

The length of a sag vertical curve should normally be determined by headlight SD requirements. When these cannot be met, sag vertical curve length ***must*** be determined by vehicle occupant ride comfort criteria.

The length of a vertical curve for a given SD is given by the following expressions (similar to the AASHTO but defining a parameter C):

(i): Where length of curve is less than the SD:

$$L = 2\,D - \frac{C}{A}$$

(ii): Where length of curve is greater than the SD:

$$L = \frac{(D^2 \, x \, A)}{C}$$

Where:

L = vertical curve length (m)
Ds = sight distance (m)
A = algebraic difference of vertical grading (%)
C = sight line constant.
Substituting the vertical curve parameter *K* for

$$K = \frac{D^2}{C}$$

K is therefore a constant for a given SD and method of defining the sight line.
The sag vertical curve sight line constant *C:*
C = ' *200 (h* + *Ds Tan q)*
Where:
h = headlight mounting height (m)
Ds = stopping sight distance (max. 150 m)
q = elevation angle of headlight beam
A mounting height of 0.75 m and zero elevation gives: *C* ' *150*

Table 16 shows the K values for sag vertical curve design in New Zealand.

Table 16. K Values for Sag Vertical Curve

Design Speed (km/h)	Headlight Sight Distance Control		Vehicle Occupant Ride Comfort Controls	
	Sight Distance (m)	C=150 K	Normal Design Situations a=0.05 g k	Special Design Situations a=0.10 g k
40	40	11	3	1.5
50	55	20	4	2
60	75	38	6	3
70	95	60	8	4
80	115	88	10	5
90	140	131	13	6
>90	150	150	>15	>8

United Kingdom

The Design Manual for Roads and Bridges states that the standard for vertical curves shall be provided at all changes in gradient Highways Agency et all, 2002). "The curvature shall be large enough to provide for comfort and, where appropriate, for SSDs for safe stopping at design speeds. For sag curves , comfort criteria apply (0.3 m/sec2 maximum rate of vertical acceleration). However, for design speeds of 70 km/h and below in unlit areas, shallower curves are necessary to ensure that headlamps illuminate the road surface for an SSD which is not more than one Design Speed below Desirable Minimum Stopping Sight." (Highways Agency, Volume 6, section 4, page 4/1). Sag curves are usually designed to the Absolute Minimum k values shown in Figure 16. According to the manual, the use of the values will normally meet the requirements of visibility; however, they always recommend to check for SSD because of the horizontal alignment, superelevation, and other treatments.

DESIGN SPEED kph	120	100	85	70	60	50	V²/R
STOPPING SIGHT DISTANCE m							
Desirable Minimum	295	215	160	120	90	70	
One Step below Desirable Minimum	215	160	120	90	70	50	
HORIZONTAL CURVATURE m.							
Minimum R* without elimination of Adverse Camber and Transitions	2880	2040	1440	1020	720	520	5
Minimum R* with Superelevation of 2.5%	2040	1440	1020	720	510	360	7.07
Minimum R* with Superelevation of 3.5%	1440	1020	720	510	360	255	10
Desirable Minimum R with Superelevation of 5%	1020	720	510	360	255	180	14.14
One Step below Desirable Minimum R with Superelevation of 7%	720	510	360	255	180	127	20
Two Steps below Desirable Minimum Radius with Superelevation of 7%	510	360	255	180	127	90	28.28
VERTICAL CURVATURE							
Desirable Minimum* Crest K Value	182	100	55	30	17	10	
One Step below Desirable Min Crest K Value	100	55	30	17	10	6.5	
Absolute Minimum Sag K Value	37	26	20	20	13	9	
OVERTAKING SIGHT DISTANCES							
Full Overtaking Sight Distance FOSD m.	*	580	490	410	345	290	
FOSD Overtaking Crest K Value	*	400	285	200	142	100	

Figure 16. Vertical curves K values. (Source: Highways Agency, 2002)

Relaxation below an absolute minimum for different kinds of roads is permitted using Design Speed Steps, depending on the category of the roads. No relaxations are allowed for motorways. For design speeds of 70 km/h and less where the sag vertical curve is illuminated, the relaxation criteria can be extended by one step, and relaxations are not permitted on the immediate approach of junctions

For countries receiving technical assistance from the British Government, the Transportation Research Laboratory (Overseas Road Note 6, 1998) mentioned that the use of the equations for a headlight height of 0.6 meters and 1 degree of angle of upward divergence of headlight beam can result in unrealistically long vertical curves and SD, perhaps in excess of the effective range of the headlamp beam, so they recommended to use the comfort criteria as shown in Figure 17.

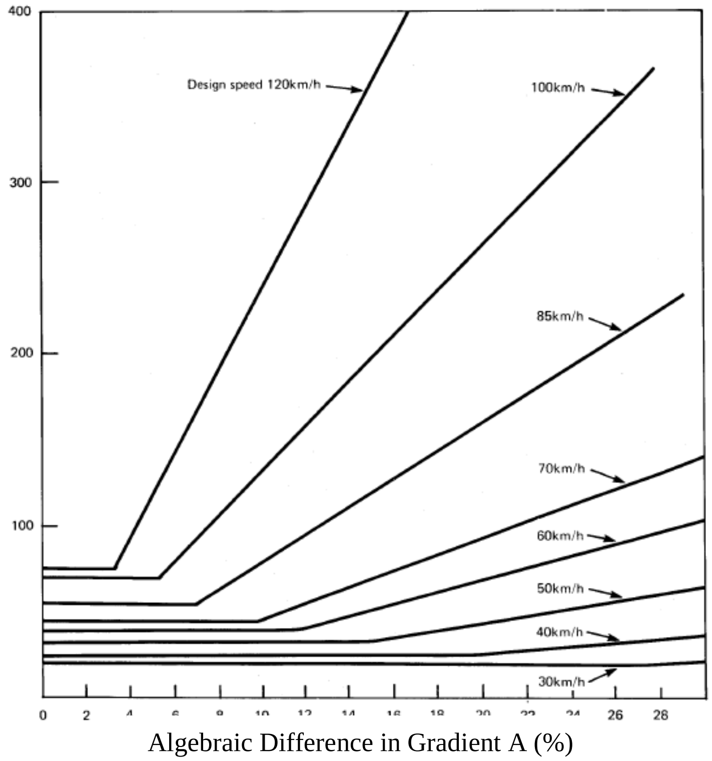


Figure 17. Length of sag vertical curves L (m) for adequate comfort (Source: Overseas Road Note 6, 1998).

Australia

The recently publish *Guide to Road Design Part 3 Geometric Design* states that sag curves are usually designed on the basis of providing reasonable SD for a headlight beam (Austroads, 2010). According to the guide "headlight SD is limited to about 120 – 150 m, which corresponds to an SSD from 80 km/h to 90 km/h, and a maneuver time of about 5 seconds at 100 km/h….. "This shortfall in-vehicle lighting, however, cannot be provided for in road design and is not a design consideration…. and the only method of achieving fully compatibility between theoretical sight distances by day and night is by roadway lighting"(Austroads 2010, page 118)

The vertical curves are in parabolic shape similar to AASHTO and the guide site three controlling factors for curves in general

- Sight distance: is a requirement in all situations for driver safety.
- Appearance: is generally required in low embankment and flat topography situations.
- Riding comfort: is a general requirement with specific need on approaches to a floodway where the length of depression needs to be minimized.

On high-speed roads consideration should be given to providing headlight sight distance
When sag curves cannot be flattened to provide desirable headlight SD, they should be designed to provide adequate riding comfort based on the criterion of 0.05 g vertical acceleration, although 0.10 g may be adopted for low standard roads. On two-lane roads, extremely long sag curves over 750 m should be avoided for drainage reasons. The *Guide to Road Design* presents a new

set of graphics for minimum size sag vertical curves, as shown in Figure 18. The graph was developed using the following criteria to determine the lower bounds:

1. Low Standard Roads – comfort criteria with a = 0.1g
2. Other Urban and Rural Roads with street lighting – comfort criteria with a = 0.05g
3. Other Urban and Rural Roads without street lighting – headlight SD with reaction time = 2.0s and coefficient of deceleration = 0.61
4. Highways and freeways:

   Minimum – headlight SD with reaction time = 2.5s and coefficient of deceleration = 0.36

   Desirable – crest curve SSD with reaction time = 2.0s and coefficient of deceleration = 0.36.

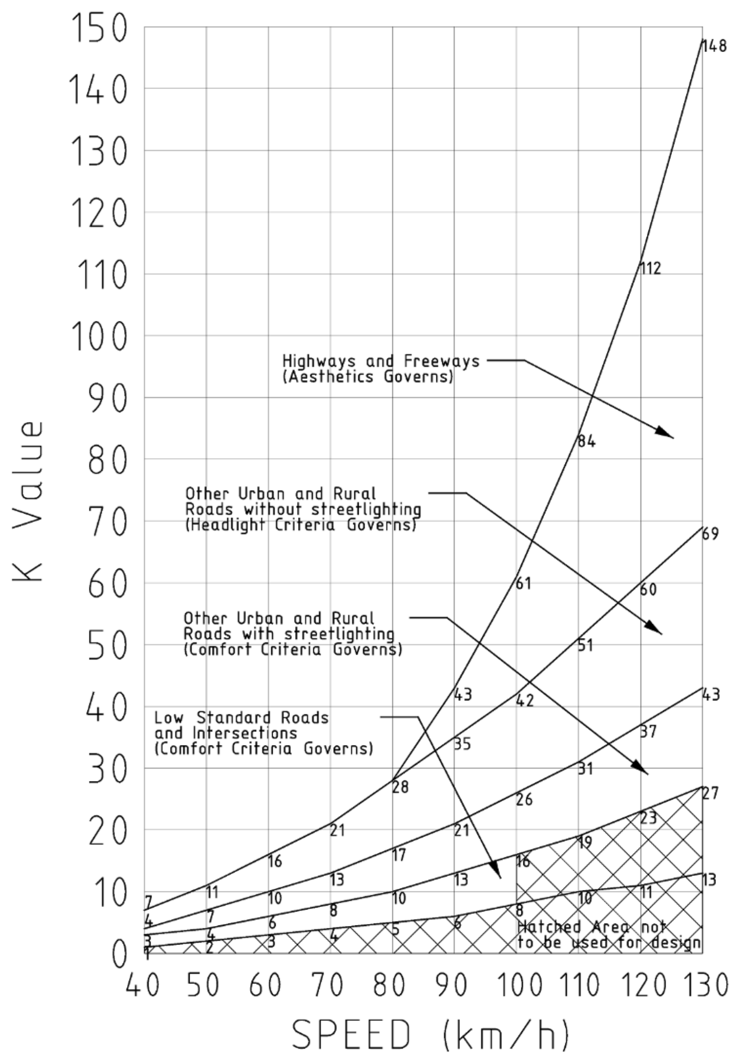


Figure 18. Minimum K values for sag curves (Source: Austroads, 2010, Figure 8.7).

Spain

In Spain, the Design Normative for sag vertical curves states that the sag vertical curves will be designed using a parabolic curve with the following equation (Ministerio de Fomento, Gobierno de Espana, 2011)

$$K_v = \frac{L}{\theta}$$

K_v=Parabolic parameter
ϴ= algebraic differences in grade percent

Sight Distance requirement

And $K_v = \frac{D^2}{(2(h - h_2 + D \cdot \tan(\alpha))}$

And where

- h_1= height over the pavement (m).
- h_2 = height of the object over the pavement (m).
- h = headlight height (m),
- α = Degree of upward divergence of the light beam from the longitudinal axis
- D = light beam distance (m).

To compute the SSD, h_1 = 1,10 m h_2 = 0,20 m; h = 0,75 m; α =1°. **Table 17** shows the minimum and desirable K values based on SD.

Table 17. Minimum and Desirable K Values for Spain

Design Speed (Km/h)	Minimum	Desirable
40	568	1374
60	1374	2636
80	2636	4348
100	4348	6685
120	6685	9801

Source: Ministerio de Fomento, Gobierno de Espana, 2011

Appearance Requirement

To check for appearance, the following length of the curve in meters must be bigger than the design speed in km/h.

L>V
Where:

L = Length of the curve (m)
V= Design speed (km/h)

Canada

The length of the sag vertical curve must be, at a minimum, the SSD (Transportation Association of Canada Geometric Design Guide for Canadian Roads, 1999; NCHRP 15-41 survey). The Transportation Association of Canada is currently working on a project comparing the guide to other geometric design guides published by similar agencies (e.g., AASHTO, Austroads, etc.) to determine if the Transportation Association of Canada Guide requires significant rewriting or needs only to be refreshed to incorporate state-of-the-art research findings.

While headlight SD is the primary criterion, additional criteria include passenger comfort, drainage control, and general appearance. The current guidelines do not have specifications for sag vertical curves underpassing a structure. The same standards apply for both lighted and unlighted sections, but they allow reduction for comfort control where conditions warrant.

Others

The *Road Safety Manual* from the World Road Association PIARC (PIARC, 2003), designed to give highway engineers a better understanding of the impacts that infrastructure has on road safety at all phases of design and operations, lists the minimum *K* values for sag vertical curves for several countries, as shown in Table 18.

Table 18. Minimum K Values for Sag Vertical Curves

Country	Design Speed (km/h)								
	40	50	60	70	80	90	100	110	120
Canada	7	11	20	25	30	40	50	55	60
France			15		22		30		42
Germany			15	20	25	35	50		100
Greece		14	19	25	33	42	52	63	75
Italy	6		12		22		39		58
Japan		7	10		20		30		40
South Africa	8	12	16	20	25	31	36	43	52
Switzerland	8	12	16	25	35	45	60	80	
USA	9	13	18	23	30	38	45	55	63

Source: PIARC, 2003

According to Krammes and Granham (1997), German guidelines are provided for maximum and minimum grade. The guidelines for sag curves are based upon general appearance. The Italian standards are set by the Consiglio Nazionale Delle Ricerche. The criteria for sag vertical curves are the same as the ones for crest vertical curves, but in exceptional cases a lower minimum radius which guarantees nighttime visibility using headlamps is permissible. The South African standards are provided by the Committee of State Road Authorities and are based upon headlight illumination distance. In Sweden, vertical curves are parabolic and sag curves and are defined as nighttime headlight systems' requirements. Sweden also defined a range of High Standards and Low Standards for selecting the minimum K value. Switzerland defines sag vertical curves based upon SD requirements.

In addition to the minimum K for sag vertical curves, the PIARC manual also lists the SSD for the different countries, as is shown in Table 19.

Table 19. Stopping Sight Distances

Country	Time	Speed (Km/h)											
		30	40	50	60	70	80	90	100	110	120	130	140
		Stopping Sight Distance											
Austria	2.0		35	50	70	90	120		185		275		380
Canada	2.5		45	65	85	110	140	170	210	250	290	220	
France	2.0		35	50	65	85	105	130	160				
Germany	2.0	25		65	85	110	140	170	210	255			
Great Britain	2.0			70	90	120			215		295		
Greece	2.0				65	85	110	140	170	205	245		
South Africa	2.5		50	65	80	95	115	135	155	180	210		
Sweden	2.0	35		70		165				195			
Switzerland	2.0	35		50	70	95	120	150	195	230	280		
USA	2.5	35	50	65	85	105	130	160	185	220	250	285	-

SUMMARY

As part of the assessment of practice in the design of sag vertical curves, a survey was administered to the 50 states plus Puerto Rico, and responses were received from 42 states. For the states that did not respond to the survey, the research team was able to gather information from five of the states' manuals; however, no information was found for three states. Forty-two of the respondent states have documented design criteria for sag vertical curves. The states that do not have documented design criteria for sag vertical curves mentioned that they followed the AASHTO guide. All the states use parabolic curves for the design of sag vertical curves and only two states (California and Louisiana) answered that they do not follow the AASHTO guidelines. In the case of the State of California, three major differences are introduced: a different computation of SSD, an increase of SSD based on sustained downgrades, and a minimum length of 10 V. The SSD was modified by Florida but only for Interstates. North Dakota is the only state that uses passenger comfort as the primary criterion for sag vertical curves and passing SD in special situations. Twenty-seven states pointed out that there are special situations where different specifications are recommended and 15 states answered that they do not use a different specification. The majority of the states using different specifications correspond to reconstruction and rehabilitation projects, the use of local City or County specifications or, when appropriate, they use AASHTO's Guidelines for Geometric Design of Very Low-Volume Local Roads.

When asked which criteria the state used when designing sag vertical curves, the responses indicated that 45 states use headlight SD, 21 use passenger comfort, 19 use drainage control, 19 use general appearance, and 13 use decision or passing SDs. All the states that used headlight SD as a criterion specified that they used the AASHTO criterion of 2 ft for headlight height and 1-degree upward divergence of the light beam from the longitudinal axis. Some states incorporate additional modifications to the headlight SD (e.g., Connecticut and California) to make a correction for grades, or change the selected design speed for some specific type of highways (e.g., Florida) or specified (as do some international standards) a lower and upper range of K based on assumed speed conditions (e.g., South Dakota). For North Dakota, passenger comfort is the primary criterion and passing SD is used as a secondary criterion in special situations. In general, the states check for the AASHTO comfort criterion based on the assumption that riding on a sag vertical curve is comfortable when centripetal acceleration does not exceed 0.3 m/s2. Other states that use comfort control criteria (e.g., Texas) specify that control criteria should be used sparingly, because of the possibility of energy shortages.

Of the 19 states that used the drainage criteria, most of them used the same criterion as AASHTO or a more exigent one.

When appearance was included as one of the criteria it was most often in the form of a required minimum length and occasionally as a specific issue (such as broken back curves in Arizona).

The decision SD is usually checked as a secondary criterion where there are complex decisions involved, as in the cases specified by North Dakota, Indiana and Illinois. Other criteria were also identified by 10 states which involved, in most of the cases, minimum length or special erosion considerations.

Sixteen of the states mentioned that they had specifications for the case of sag vertical curves underpassing a structure. The states that have incorporated this criterion follow AASHTO or a similar formula with slightly modified parameters. Most of the states do not have specific design criteria for continuously lighted sections, but lighting can be considered as a mitigation factor in several states. Also note that several states allow shorter curves, or occasionally the sag vertical curve can be avoided, but all of these cases fall under exemptions.

All the states responded that they have not conducted any studies regarding design or safety of vertical design curves. Twenty-five states do not specifically have a field on their accident records indicating if the accident occurred in a sag vertical curve. In only seven states (Alabama, Arizona, Michigan, Virginia, Utah, West Virginia and Washington) can accident records occurring in sag vertical curves be identified; most of the time this can only be determined indirectly.

Criteria and K values for several countries were obtained with different degrees of detail depending on information availability; the countries included Canada, England, New Zealand, Spain, and Sweden and Australia. There are some differences between U.S. standards and those of some European countries, one being the use of circular curves in some of the European countries instead of parabolic vertical curves. In addition, for some countries, headlight SD is the dominant criterion while, for others, comfort or appearance is a more prevalent criterion. Also, in some cases (e.g., New Zealand), headlight SD is also limited and maximum rates of vertical acceleration vary from 0.3m/s2 to 0.05g to 0.1 g.

Exceptions from the absolute minimum length are permitted and are computed as using Design Speed Steps (e.g., as in Ireland) or minimum and desirable K values (e.g., as in Spain). Australia recently modified the new guide and, depending on the category of road, the governing criteria as well.

CHAPTER 5 POTENTIAL CHANGES TO THE AASHTO POLICY

Based on the results of the literature review and the practitioner survey, modifications to the AASHTO methodologies can be considered. As there were very few exceptions to the AASHTO methodologies, the confines of the existing methods must be considered.

Three alternatives are proposed below in dealing with the headlight issue: extend sag curve length, increase deceleration rate, or decrease design speed at locations where the minimum requirement for SD is not met.

The applicability of these potential changes will be considered at the completion of the experimental process.

SOLUTION 1: EXTEND SAG CURVE LENGTH

Due to the angle change, the road segment illuminated by the headlight is shorter than before. To ensure a timely stop within the visible distance, an extension of sag curve is needed to lengthen the headlight SD to the minimum SSD. The SDs illuminated by the headlight (assuming $S < L$) are calculated using the equation below:

$$\boldsymbol{S} = \frac{\mathbf{200} * \tan(\boldsymbol{\alpha}) * \boldsymbol{L} + \sqrt{(\mathbf{200} * \tan(\boldsymbol{\alpha}) * \boldsymbol{L})^2 + \mathbf{1600} * \boldsymbol{A} * \boldsymbol{L}}}{\mathbf{2}\boldsymbol{A}} \quad \mathbf{(4)}$$

The results are listed in Table 20. As can be seen, the SD at the speed of 80 mph decreases nearly 20% when the angle is 0.75.

Table 20. Sight Distance Affected by Headlight Up Angle

Design Speed	Angle 1	Angle 0.95	Angle 0.90	Angle 0.85	Angle 0.80	Angle 0.75	Angle 0.70	Angle 0.65	Angle 0.60
15 mph	80	78.97	77.95	76.94	75.94	74.95	73.97	73.00	72.04
20 mph	115	113.09	111.20	109.33	107.49	105.67	103.87	102.09	100.34
25 mph	155	151.89	148.82	145.79	142.80	139.85	136.95	134.08	131.26
30 mph	200	195.37	190.80	186.29	181.84	177.46	173.15	168.90	164.73
35 mph	250	243.52	237.12	230.81	224.60	218.47	212.45	206.53	200.71
40 mph	305	296.34	287.80	279.38	271.08	262.90	254.86	246.97	239.21
45 mph	360	349.07	338.27	327.62	317.13	306.79	296.63	286.65	276.86
50 mph	425	411.27	397.71	384.33	371.14	358.15	345.37	332.82	320.51
55 mph	495	478.17	461.54	445.12	428.93	412.98	397.28	381.87	366.74
60 mph	570	549.78	529.78	510.02	490.52	471.31	452.40	433.82	415.59
65 mph	645	621.32	597.89	574.73	551.86	529.32	507.12	485.30	463.88
70 mph	730	702.35	674.97	647.89	621.14	594.76	568.76	543.20	518.10
75 mph	820	788.09	756.48	725.20	694.29	663.77	633.69	604.09	575.02
80 mph	910	873.80	837.92	802.39	767.26	732.56	698.34	664.65	631.54

To ensure a long enough SD, the headlight SDs at an angle of 1º, which are equal to the stopping SDs, were used in equation (2) to re-calculate the curve lengths needed under different uplight angles. The updated curve lengths are shown in Figure 19. As can be seen, when the design speed is low and the *A* is small, minimum lengths of sag curve at different headlamp angles are more similar. The curve lengths spread to the right dramatically with the increasing of speeds and grades.

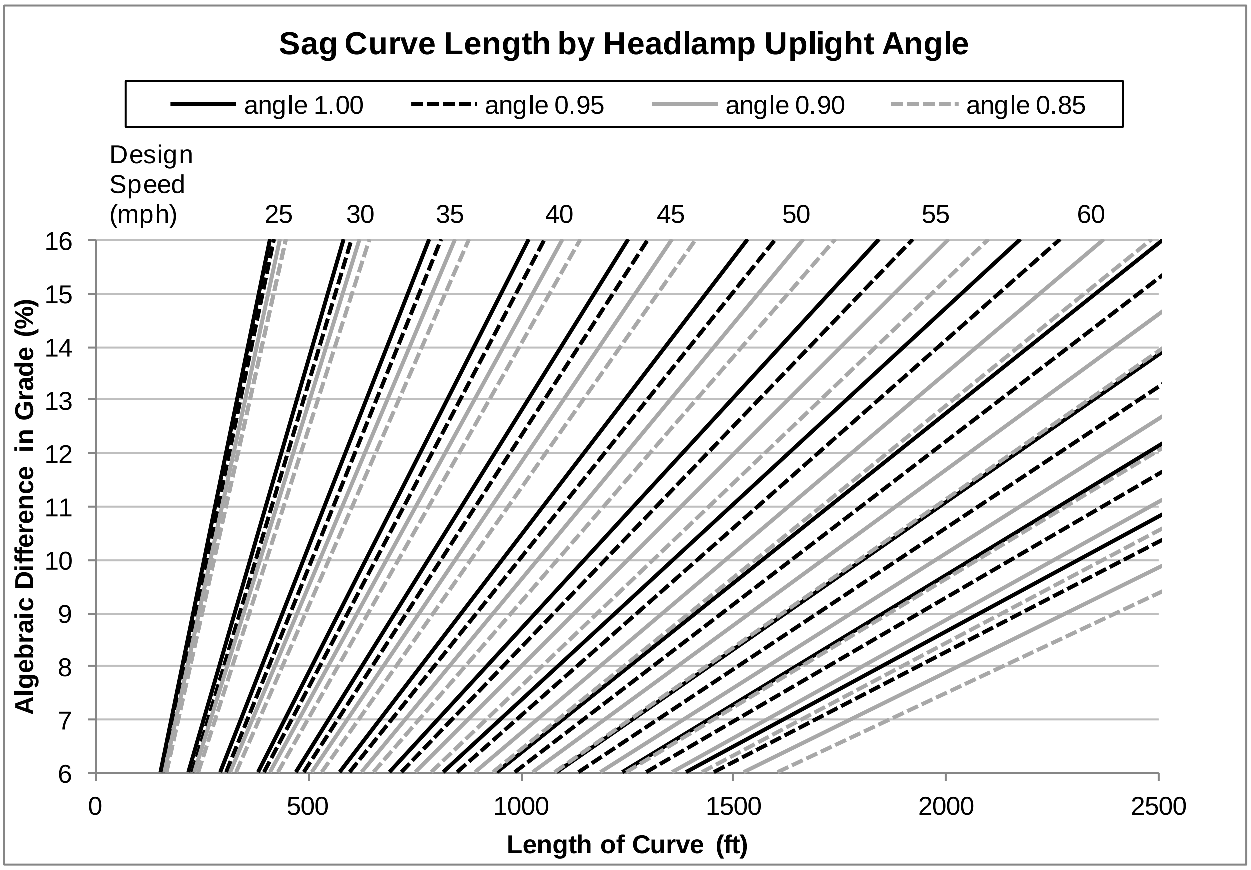


Figure 19. Curve lengths by headlamp uplight angle.

Extending sag curve lengths, however, is not feasible at certain locations due to terrain, drainage, or financial limitations. Therefore, two other approaches were proposed.

The following two solutions were proposed as alternatives in the case that it was found that the actual length was not sufficient and needed to be modified. The first was in based on evidence that the parameters used to compute the length of the vertical curve do not reflect some new research (less reaction time that 2.5 sec, maximum acceleration greater than 11.2ft/s^2, and different friction values for different types of roads). The second solution was a practical solution, that under the same expectation that the length curve is not sufficient, the more direct approach to solve a specific problem was to reduce the speed as a countermeasure. However, it must be recognized that a change in the accepted deceleration rate, perception-reaction time or pavement friction will have implications in the guide that go beyond the design of sag vertical curves.

SOLUTION A.1: INCREASE DECELERATION RATE

According to AASHTO, the current SSD assumes that: 1) the reaction time is 2.5 s, and 2), the deceleration rate is 11.2 ft/s^2. These assumptions are made because "…a 2.5 second brake reaction time for stopping sight situations encompasses the capabilities of most drivers including those of older drivers…" and "…most vehicle braking systems and the tire-pavement friction of most roadways are capable of providing of at least 11.2 ft/s^2." (AASHTO, 2004) Due to changes of the visible distance ahead of vehicles incurred by headlight angle changes, the vehicles are required to stop within a shorter distance. Because of this, a larger deceleration rate is desired. Using the equation below, the deceleration rate needed to make a timely stop is calculated:

$$\boldsymbol{a} = \frac{\mathbf{1.075} * \boldsymbol{V}^{\mathbf{2}}}{(\boldsymbol{S} - \mathbf{1.47} * \boldsymbol{V} * \boldsymbol{t})} \tag{5}$$

Where is the decreased headlight SD, *V* is the design speed, and *t* is the reaction time. The results are plotted in Figure 20. As can be seen, the deceleration rates at 1° are all under the assumed criterion, 11.2 ft/s^2. With decreased uplight angles, the required deceleration level increases rapidly. At a speed of 65 mph, the deceleration rate needed at the angle of 0.75° increases to 15.638 ft/s^2, which is almost 40% higher.

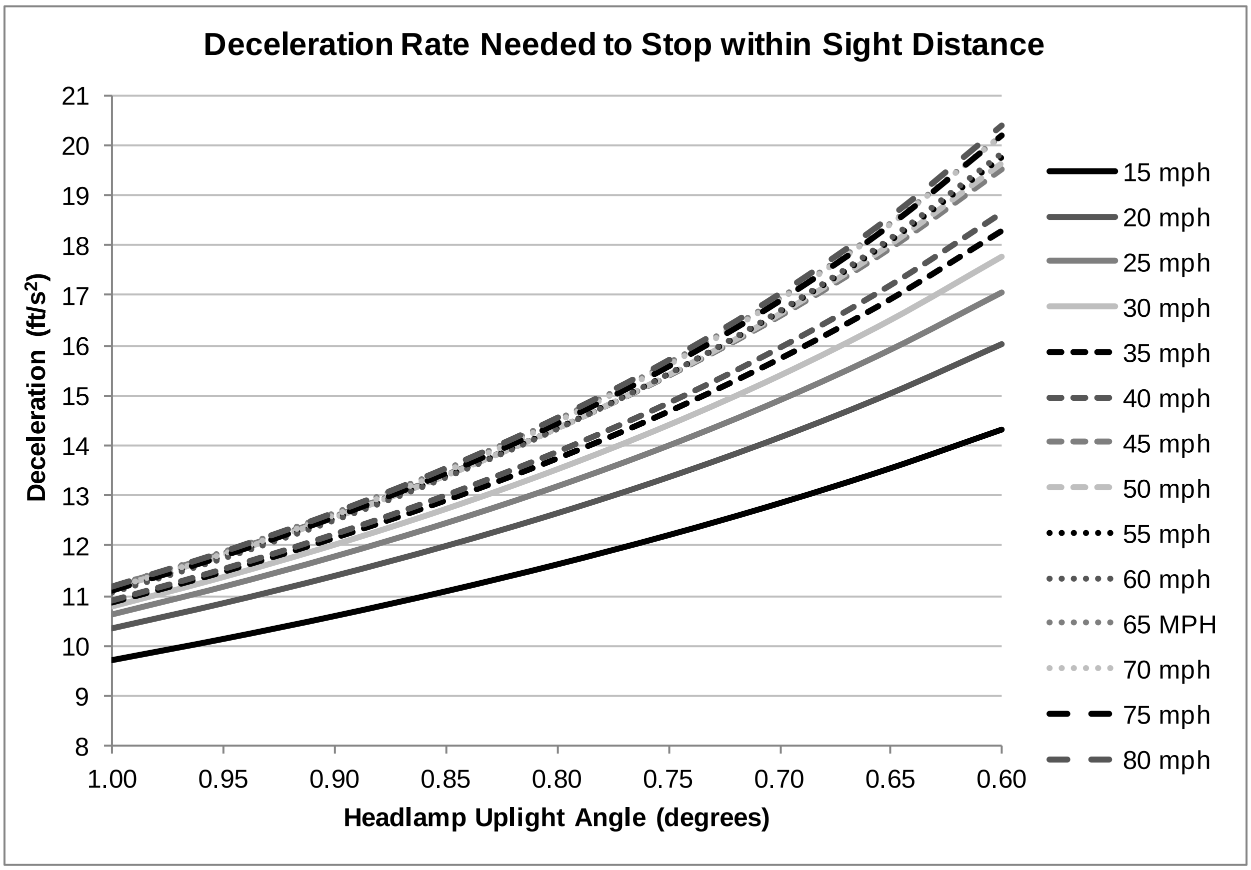


Figure 20. Desired deceleration rate by design speed.

Although increasing deceleration rate can be obtained in some cases, given a satisfactory road surface, tire quality, and weather condition, it is not always an efficient solution. A third solution is therefore proposed.

SOLUTION A.2: DECREASE DESIGN SPEED

When extending curve or increasing deceleration rate are both infeasible, another alternative is to decrease design speed on partial segments on a highway. Equation (6) below is used to calculate the design speed:

$$\boldsymbol{V} = \frac{-\mathbf{3.675} * \boldsymbol{a} + \sqrt{(\mathbf{3.675} * \boldsymbol{a})^{\mathbf{2}} + \mathbf{4.3} * \boldsymbol{d} * \boldsymbol{a}}}{\mathbf{2.15}} \quad \textbf{(6)}$$

Where *a* is the deceleration rate and *d* is the headlight SD under different headlight angles.

The results are exhibited in Table 21. As can be seen, at the angle of 0.75 and the original design speed of 65 mph, to achieve a timely stop within a shorter distance (529.32 ft in Table 21), the design speed needs to be decreased to 58 mph (a decrease of 10.8 percent) to guarantee a timely stop.

Table 21. Speeds Changes for Decreased Headlight Sight Distance

Design Speed at the Angle of 1	Angle 0.95	Angle 0.90	Angle 0.85	Angle 0.80	Angle 0.75	Angle 0.70	Angle 0.65	Angle 0.60
15 MPH	15	15	15	14	14	14	14	14
20 MPH	20	20	19	19	19	19	18	18
25 MPH	25	24	24	24	23	23	23	22
30 MPH	30	29	29	28	28	27	27	26
35 MPH	34	34	33	33	32	31	31	30
40 MPH	39	38	38	37	36	35	35	34
45 MPH	44	43	42	41	41	40	39	38
50 MPH	49	48	47	46	45	44	43	42
55 MPH	54	53	51	50	49	48	47	45
60 MPH	59	57	56	55	53	52	51	49
65 MPH	64	62	61	59	58	56	54	53
70 MPH	68	67	65	63	62	60	58	57
75 MPH	73	71	70	68	66	64	62	60
80 MPH	78	76	74	72	70	68	66	64

ISSUES FOR THE POTENTIAL GUIDELINE RECOMMENDATIONS

1. The changes in headlight angles do affect the design of sag vertical curves due to a decreasing of SD. The guideline in AASHTO needs to incorporate these changes and provide more details under situations in which the requirement for SD is not satisfied.
2. The discussions and recommendations in this section assume that even with the angle changes, the headlight SD is always longer than SSD on flat ground. According to the research by the team members, for some types of headlights, this assumption may not be valid when design speeds are in the higher end. In those cases, the *S* used in the equations above needs to be replaced by "minimum (headlight sight distance, stopping sight distance)."
3. In addition to SSDs on a regular sag vertical curve, AASHTO defines SDs through undercrossings as:

   When *S* (in feet) is less than *L* (in feet)

$$\boldsymbol{L = \frac{AS^2}{800(C-5)}} \qquad \textbf{(7)}$$

   When *S* (in feet) is greater than *L* (in feet)

$$\boldsymbol{L = 2S - (\frac{800(C-5)}{A})} \qquad \textbf{(8)}$$

   Where *C* is the bridge clearance.

As can be seen, the major concern here is the blockage of sight by the overpass. Therefore, the change of uplight angle of headlights will not affect the design of sag curve through undercrossings as long as the curve meets the minimum length requirement discussed above.

CHAPTER 6 VISIBILITY EXPERIMENTS

Two human-subjects experiments were conducted to determine the effects of headlamps and sag vertical curves on visibility. The first experiment, called the Smart Road study, examined the effects of varying types of headlamps. The second experiment, called the Public Road study, examined the effects of varying sag vertical curves. The results of these experiments were then used to determine the practicality of the proposed policy changes suggested in Chapter 5. The methods, results, and discussion of the Smart Road study are described below, followed by that of the Public Road study.

SMART ROAD STUDY

The purpose of the Smart Road study was to determine if modern headlamp designs have diminished visibility in sag vertical curves as compared to the more traditional headlamps likely used in the development of AASHTO's guidelines.

Smart Road Experimental Design

This experiment took place on the Virginia Smart Road, and compared the performance of several different types of headlamps in sag vertical curves. The study used a 6 (Headlamp) x 3 (Object) x 4 (Sag Vertical Curve) mixed-factors design. The six headlamps used either a halogen or HID light source, and used either a standard, VOL, or VOR beam pattern. One headlamp used a high beam setting. The objects which participants identified were either a pedestrian dressed in denim clothing, a 7-inch-square piece of wood painted gray (called a target), or a speed limit sign. Participants identified objects on four types of sag vertical curves: flat (i.e., no curve), large curve, small curve, and a sag vertical curve which also had a horizontal curve to the left termed the "left curve." Table 22 shows the design matrix. Cells marked with an "X" represent scenarios which were tested. Every participant observed every test scenario.

Table 22. Smart Road Study Experimental Design Matrix

	Pedestrian				Target				Speed Limit Sign			
Headlamp	Flat	Large Curve	Small Curve	Left Curve	Flat	Large Curve	Small Curve	Left Curve	Flat	Large Curve	Small Curve	Left Curve
HHB	X	X	X	X	X	X			X			
HLB	X	X	X	X	X	X			X			
VOLHID1	X	X	X	X	X	X			X			
VOLHID2	X	X	X	X	X	X			X			
VORHAL	X	X	X	X	X	X			X			
VORHID	X	X	X	X	X	X			X			

HHB - halogen high beam; HLB - halogen low beam; VOLHID – Visually Optically Aligned Left HID; VORHAL - Visually Optically Aligned Right Halogen; VORHID - Visually Optically Aligned Right HID

Independent Variables

Several independent variables were manipulated or controlled for this experiment. They are listed below.

Between-Subjects Variables

- Gender (2 levels): Female, Male. The gender independent variable was chosen in order to generalize the results of this study to a broad user population. This factor was used for balance only; it was not used in the data analysis.
- Age (2 levels): Younger (21-34), Older (65+). The younger and older age groups were selected to investigate the changes in vision and perception that may occur with increasing age.

Within-Subjects Variables

- Headlamp (6 levels): Halogen High Beam (HHB), Halogen Low Beam (HLB), two Visually Optically Aligned Left HIDs (VOLHID1 and VOLHID2), Visually Optically Aligned Right Halogen (VORHAL), and Visually Optically Aligned Right HID (VORHID). The six different headlamps were selected to represent an array of the most common types of headlamp light sources and beam patterns.
- Object (3 levels): Pedestrian, Target, and Speed Limit Sign. The pedestrian and target objects were selected to represent objects a motorist may encounter on or near the roadway that may require action to avoid. The speed limit sign object was used to determine if the amount of uplight from the different headlamps had an effect on a driver's ability to read signs.
- Sag Vertical Curve (4 levels): None (i.e., Flat), Large Curve, Short Curve, and Left Curve. The three different sag vertical curves selected were chosen based on what curves were available on the Smart Road test track. The non-curved, or flat, area was selected as a point of comparison for the sag curves.

Dependent Variables

Detection Distance

The distance at which a participant could identify an object was recorded as a measure of the visibility of the object. Participants were instructed to verbally identify objects as they drove. Participants would say "pedestrian" or "target" aloud depending on the object being presented. At that moment, an in-vehicle experimenter would flag the data with a button press. When the vehicle reached the object, the in-vehicle experimenter would again flag the data with a button press. Later analysis determined the distance traveled between these two points, and this was termed the "detection distance." Figure 21 illustrates the two points at which the data was flagged.

Detection distance as defined in this report may be more closely related to recognition distance in that participants had to identify what an object was, rather than simply detect that *something* was there. However, as the only two objects used in this study were quite different in size, shape, and color, it is likely that recognition in this study was a relatively quick process.

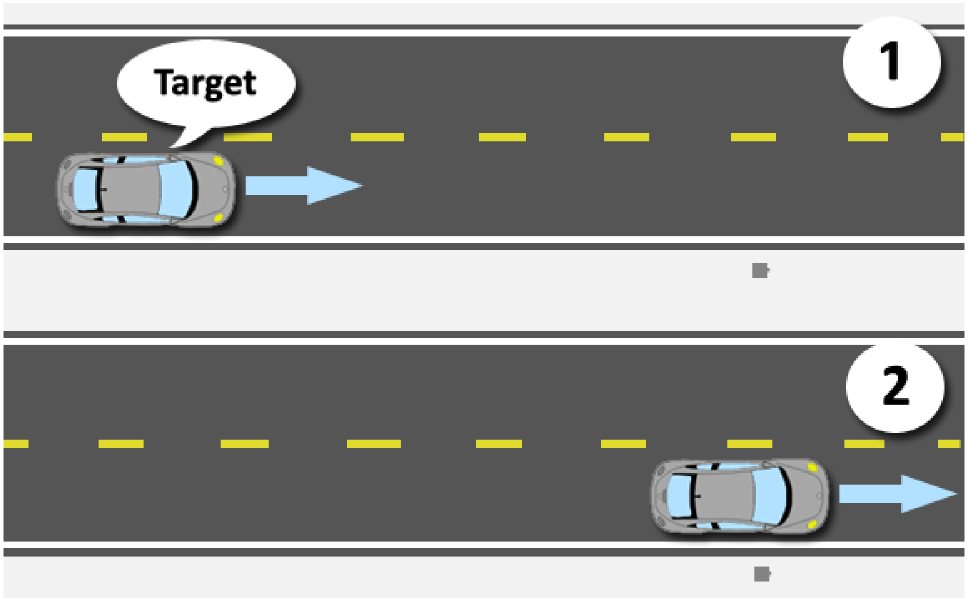


Figure 21. Determining detection distance.

The retroreflective nature of the speed limit signs made them visible from great distances. Therefore, detection distance for the signs was measured differently. Rather than identify when they could see the signs, participants were instead instructed to read aloud the number on the sign as soon as they could read it. Participants would say aloud "35" or "55" depending on the sign being presented. The distance between this point and the point at which the vehicle reached the sign determined the detection distance for the sign.

Participants

Twenty-five participants were selected to take part in this study. Participants were selected from two age categories: younger (18-34 years old) and older (65+). Six younger males, six older males, six younger females, and six older females participated. Recruitment occurred through the Virginia Tech Transportation Institute (VTTI) participant database as well as word-of-mouth. A general description of the study was provided to the subjects over the phone before they decided if they were willing to participate. If they were interested, subjects were then screened with a verbal questionnaire to determine whether they were licensed drivers and whether they had any health concerns that should exclude them from participating in the study. If subjects were determined to be eligible for the study, they were then scheduled to come to VTTI for participation. When subjects arrived at VTTI, they read and signed an informed consent form. Subjects were paid $20/hr and were allowed to withdraw at any point in time, with compensation adjusted accordingly.

Participants' Age and Visual Capabilities

The ages of the younger participants ranged from 21 to 26 years old, with a median age of 22 years. The older participants ranged in age from 66 to 70 years old, with a median age of 67 years. All participants passed a color-blindness test, with only two participants giving a single incorrect response each. Table 23 presents the distribution of visual acuity scores. A minimum of 20/40 was required for participation. Participants were allowed to wear corrective lenses if they indicated that they normally wear them while driving.

Table 23. Visual Acuity Scores

Visual Acuity (Snellen)	Number of Participants
20/15	4
20/20	8
20/25	4
20/30	7
20/40	2

Participants' visual acuity was also measured in the presence of glare using a Brightness Acuity Tester (BAT). The distribution of visual acuity scores for each eye and level of glare are presented in Table 24.

Table 24. Visual Acuity in the Presence of Glare

	No Glare		Low Glare		Med Glare		High Glare	
Acuity Score	**Left Eye**	**Right Eye**	**Left Eye**	**Right Eye**	**Left Eye**	**Right Eye**	**Left Eye**	**Right Eye**
20/13	1	1	1	1	1	1	1	1
20/15	0	0	0	0	2	0	1	0
20/20	3	4	6	4	4	4	0	2
20/25	6	6	5	5	4	4	6	3
20/30	6	4	6	6	2	5	5	3
20/40	6	7	1	5	5	5	4	7
20/50	3	0	5	1	5	4	4	3
20/70 and worse	0	3	1	3	2	2	4	6

Facilities and Equipment

Smart Road Test Track

This experiment was conducted on the Virginia Smart Road; a 2.2 mile-long, restricted-access test facility. The Smart Road provided three different sag vertical curve geometries. The first is on the primary roadway where the Smart Road Bridge transitions to the flatter turnaround area (Figure 22). The second curve is on an access road which intersects the main roadway (Figure 23). Here, a shallower curve is evident (the pictured gate was open during the experiment). A third curve was located in the upper turnaround (Figure 22). This section of roadway also had a horizontal curve.

Figure 22. Primary sag vertical curve on the Smart Road.

Figure 23. Secondary sag vertical curve on the Smart Road.

The measures of the large curve were found in the design documents for the Smart Road. The measurements of the short and left curves were made using Global Positioning System (GPS) data recorded using a GPS-enabled vehicle. The data were processed in ArcGIS™ and ArcMap™ 10 software to generate the elevation, showing the profile of the curves. These profiles were printed, and the tangent lines were found visually using a straight edge. The slopes of the tangent lines were calculated to determine the algebraic change in grade while the horizontal distance between the two tangent points was used to determine the length of the curves. Table 25 summarizes this information. It also shows the minimum K value based on design speed, and the actual K value – called K reality or K_R - based on the grade and length measurements, or design documents.

Table 25. Sag Vertical Curve Measurements

Curve	Design Speed (mph)	Minimum K	Algebraic Change in Grade, *A* (%)	Length, *L* (ft)	K_R (*L/A*)
Short Curve*	25	26	4.67	200	43
Left Curve*	35	49	5.53	215	39
Large Curve	62	148	9.41	2297	244

*The design speeds were unknown for these curves, and were estimated by the research team.

Visibility Objects

Participants were asked to detect pedestrians and small targets while performing the study. Pedestrians were on-road experimenters dressed in denim-colored surgical scrubs (shown in Figure 24. The targets were 7” square pieces of wood with a small tab on one side, painted in 18% reflectance gray paint as shown in Figure 25. Pedestrians and targets appeared on the shoulder of the roadway, closest to the participant’s travel lane, approximately two feet from the lane’s edge-line. Pedestrians faced into the roadway to the roadway, and stepped backward away from the road when the participant vehicle came within a close proximity. Targets stood upright in a small wooden base which was also painted gray, and the face of the target was pointed parallel with the roadway toward the approaching vehicle.

Figure 24. Example of Pedestrians used in the Visibility Experiment.

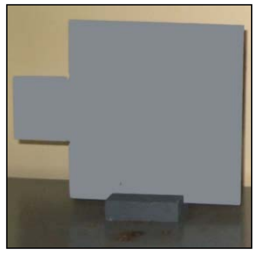


Figure 25. Example of Targets used in the Visibility Experiment.

Headlamps and Test Vehicles

Participants drove either a 1999 or 2000 model Ford Explorer equipped with a special headlamp mounting system. The mounting system allowed an experimenter to quickly change the headlamps during the study, so that participants could perform the study with each set of headlamps without having to switch vehicles.

The headlamps used in the study are summarized in Table 26 below. The vehicle from which the headlamps originated is listed in the table, however all headlamps were placed only on the two Ford Explorers for this experiment. These were selected as being representative of the most common types of headlamps, which include headlamps with halogen or HID light sources, and with standard, VOL, or VOR beam patterns.

Table 26. Headlamps

Headlamp Abbreviation	Description	Original Vehicle	Photo
HHB	Standard Halogen High Beam	2000 Ford Explorer	
HLB	Standard Halogen Low Beam	2000 Ford Explorer	
VOLHID1	Visually Optically Aligned Left HID	2001 Mercedes S500	
VOLHID2	Visually Optically Aligned Left HID	2003 Mercedes E320	
VORHID	Visually Optically Aligned Right HID	2003 Lincoln Navigator	
VORHAL	Visually Optically Aligned Right Halogen	2003 Lincoln Navigator	

The test vehicles were also equipped with data acquisition systems (DAS). The DAS recorded video both inside and outside of the vehicle and button inputs from the in-vehicle experimenter, as well as network data such as speed and distance. Detection distance was determined by analysis of this data.

Smart Road Experimental Method

Participants were initially contacted and screened on the phone using an internal VTTI database of persons who had expressed interest in participating in research studies. When participants arrived at VTTI for participation, they first read and signed the informed consent. Participants then filled out a W9 tax form and a health history questionnaire. These were followed by vision tests for acuity, contrast sensitivity, and color blindness. Participants were only excluded from participation if visual acuity was less than 20/40 (the legal minimum to hold a Virginia driver's license), or if they had taken any substance which might impair their ability to drive.

Participants were scheduled in pairs, with each driving a different test vehicle. Once the paperwork and vision tests were complete, the participants were escorted to their assigned vehicle by an in-vehicle experimenter. Participants were then instructed to drive to the Smart Road. Once on the road, participants drove a practice lap in order to familiarize themselves with the road, the points at which they would be turning around, and where they would be stopping to have the headlamps on the vehicle changed. No detection tasks occurred during the practice lap. Figure 26 shows the layout of the Smart Road and the object and curve locations. Objects were only present when the participant vehicle was in the nearest travel lane (i.e., when the object was on the driver's right hand side).

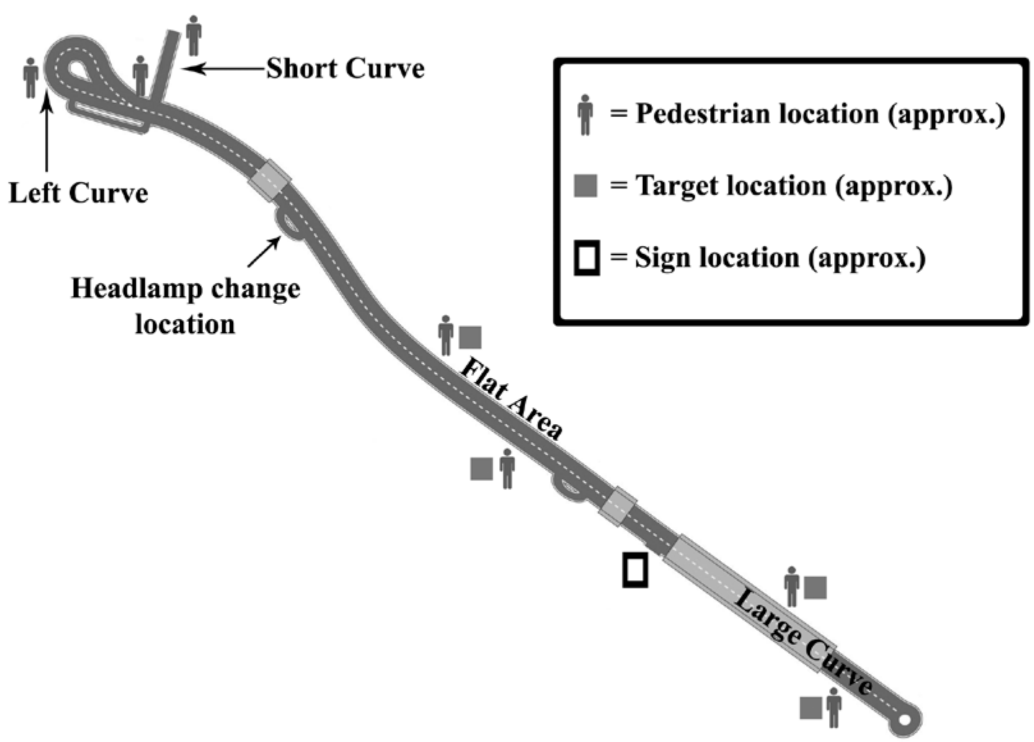


Figure 26. Object and curve locations.

Participants drove 2 laps with each headlamp for a total of 12 laps. Starting from the headlamp changing area, participants drove through the flat area and across the large curve. They then turned around and traveled through those areas again in the opposite direction. Participants then turned right at the intersection onto the access road. They drove across the short curve and into a gravel parking lot. Participants then turned around, and drove back onto the Smart Road, crossing the short curve again. Participants then turned right onto the Smart Road and traveled through the upper loop where the left curve was located. Next, participants traveled to the end of the road, crossing the flat area and large curve again. Finally, after crossing the large curve and flat area traveling back up the road, participants stopped in the headlamp changing location to have the headlamps changed. This pattern was repeated for each of the six headlamps. Pedestrians in the short and left curves were seen only once for each headlamp.

The timing of the two participant vehicles was such that the second participant was beginning a lap as the first participant drove past the headlamp changing area on his/her way up toward the short curve. The first participant would then wait at the end of the upper loop until the second vehicle was turning onto the access road. Once the second participant turned, the first would proceed with the next lap. This way, the vehicles never passed each other during data collection.

As participants drove, they would verbally identify the objects (pedestrians or targets) as they encountered them, and read aloud the number on the speed limit sign as soon as they could read it. The in-vehicle experimenters flagged these moments in the data with a button press. They also flagged the point at which the vehicle reached the object or sign that was detected.

Once both participants had completed all 12 laps, they were instructed to exit the Smart Road and return to VTTI. There, they were paid for their participation and given a receipt and a copy of the informed consent. Participants were compensated at a rate of $20 per hour.

Presentation Orders

Two factors limited the ability to fully balance the presentation of the headlamps. The first was the fact that the two vehicles which were being used simultaneously by participants had to share the headlamps. Thus, the headlamps assigned to one vehicle were dependent upon which headlamps were already assigned to the other vehicle. The second factor was that two of the headlamp levels used the same physical headlamps: high beam and low beam halogens. Thus, for efficiency, those two headlamp levels were always paired, though the order in which they appeared was balanced. Because of these factors, four semi-balanced orders were used (Table 27). Each participant performed the experiment with every headlamp; however, not every headlamp was used in every position (e.g., VOR HID did not appear in the second or fourth positions).

Table 27. Headlamp Presentation Orders

Order 1	Order 2	Order 3	Order 4
Halogen Low Beam	VOR Halogen	VOR HID	VOL HID 1
Halogen High Beam	VOL HID 2	Halogen High Beam	VOR Halogen
VOL HID 1	Halogen Low Beam	Halogen Low Beam	VOR HID
VOL HID 2	Halogen High Beam	VOR Halogen	Halogen High Beam
VOR HID	VOL HID 1	VOL HID 2	Halogen Low Beam
VOR Halogen	VOR HID	VOL HID 1	VOL HID 2

Not all objects were presented in every curve. Signs only appeared on the flat section of roadway. Pedestrians and small targets were presented and counterbalanced on the flat section and in the main sag vertical curve on the Smart Road, termed the Large Curve. Because participants only observed objects in the Short and Left Curves once for each headlamp, only pedestrians were presented so that comparisons could be made between headlamps. Table 28 shows how many times each object was presented in each curve for each participant.

Table 28. Number of Object Presentations by Curve per Participant

	Pedestrian	Target	35mph Sign	55mph Sign
Flat	12	12	6	6
Large Curve	12	12	0	0
Short Curve	6	0	0	0
Left Curve	6	0	0	0

Smart Road Data Analysis

To investigate the importance of different aspects of the headlamps, three analyses of covariance (ANCOVA) with a significance level of 95% ($\alpha = 0.05$) were used. The first analysis treated each of the six headlamps as its own factor. This was termed the headlamp analysis. The second analysis investigated the difference between halogen and HID light sources. This was termed the source analysis. Finally, the third analysis investigated the differences among different beam patterns (standard, VOL, and VOR). This was termed the pattern analysis. Table 29 shows how the headlamps were grouped by light source or beam pattern. The halogen high beams were excluded from the source and pattern analyses.

Table 29. Headlamp Grouping by Light Source and Beam Pattern

<table>
<tr><th></th><th colspan="3">Beam Pattern</th></tr>
<tr><th>Light Source</th><th>Standard</th><th>VOL</th><th>VOR</th></tr>
<tr><th>Halogen</th><td>HLB</td><td></td><td>VORHAL</td></tr>
<tr><th>HID</th><td></td><td>VOLHID1
VOLHID2</td><td>VORHID</td></tr>
</table>

The speed at which participants drove through the sag vertical curves varied. Participants drove two speeds for the large curve and flat roadway sections (45 and 60 mph). Due to the nature of the roadway, the speed at which participants drove through the short curve and left curve was left to each participant's discretion, and was generally between 25 and 35 mph. Because speed may have an impact on detection distance, vehicle speed was used as the covariate in each of the three analyses. A separate analysis was done for the detection of the speed limit signs because they did not appear in any sag vertical curve.

SMART ROAD STUDY RESULTS

Analysis of Headlamps

Table 30 shows the ANCOVA results of the headlamp analysis for the detection of pedestrians and targets. Significant factors are marked by an asterisk.

Table 30. ANCOVA Results for the Headlamp Analysis

Source	DF	Type III SS	Mean Square	F Value	Pr > F	Sig
Age	1	420875.43	420875.43	13.48	0.0013	*
Headlamp	5	1491752.2	298350.44	34.69	<.0001	*
Age*Headlamp	5	58050.987	11610.197	1.35	0.2485	
Object	1	57821.365	57821.365	24.16	<.0001	*
Age*Object	1	234.333	234.333	0.1	0.7572	
Curve	3	1673550.1	557850.03	119.7	<.0001	*
Age*Curve	3	60794.571	20264.857	4.35	0.0073	*
Headlamp*Object	5	126716.48	25343.296	5.12	0.0003	*
Age*Headlamp*Object	5	3439.1796	687.8359	0.14	0.9828	
Headlamp*Curve	15	534234.23	35615.615	17.14	<.0001	*
Age*Headlamp*Curve	15	57150.55	3810.0367	1.83	0.0292	
Object*Curve	1	148317.29	148317.29	60.48	<.0001	*
Age*Object*Curve	1	6540.3005	6540.3005	2.67	0.1161	
Headlamp*Object*Curve	5	131133.58	26226.716	4.99	0.0004	*
Age*Headlamp*Object*Curve	5	23842.667	4768.5334	0.91	0.4785	
Total	71	4794453.2				
** p < 0.05 (significant)*						

Age was found to be a significant factor. The mean detection distance for younger participants (216 ft) was significantly longer than that of older participants (178 ft). This result is expected as visual ability tends to decline with age.

Headlamp was also found to be significant. Figure 27 shows the mean detection distance for each headlamp along with the Student-Newman-Keuls (SNK) grouping. The SNK test is a pairwise comparison which looks for a significant difference between each possible pair of factor levels. Factor levels with different SNK groupings (i.e., letters) are significantly different from one another. Factor levels with the same grouping are not significantly different. The HHBs had a significantly longer mean detection distance than all of the low beam headlamps. Of the low beam headlamps, only the VOLHID2s had a significantly different (better) performance.

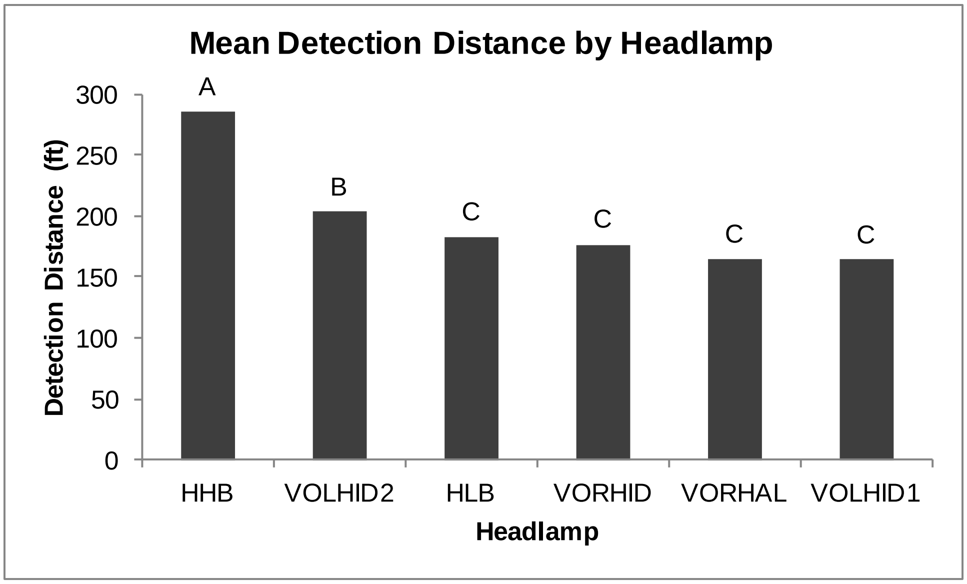


Figure 27. Mean detection distance by headlamp.

Object was also found to be a significant factor, with the mean detection distance for targets (216 ft) significantly longer than that of pedestrians (184 ft). This result may have been influenced by the fact that targets were only seen in the flat area and in the large curve, where pedestrians were also seen in the short curve and the left curve. The shorter detection distances in these areas likely brought the mean distance for pedestrians down.

Figure 28 shows the significant effect of curve on detection distance. As expected, mean detection distance in the flat area was significantly longer than for any of the sag vertical curves. Of the three curves, the large curve had a significantly longer mean distance than did the short curve which, in turn, had a significantly longer mean distance than did the left curve.

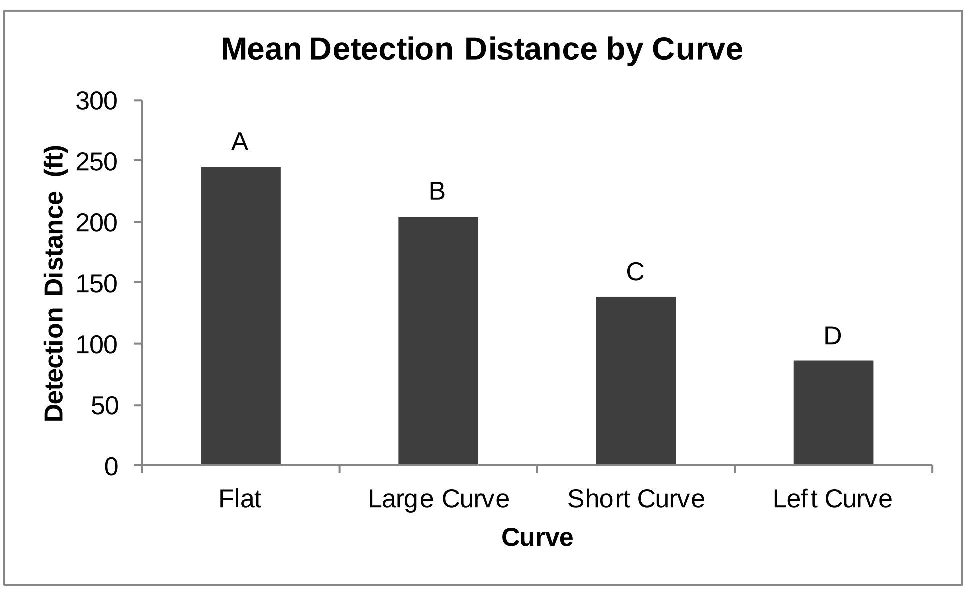


Figure 28. Mean detection distance by curve.

A significant interaction was found between curve and age. Younger participants had significantly longer detection distances than did older participants on the flat roadway, and in every curve. However, the difference between younger and older participants diminished as the curves got smaller. This is expected as the overall visibility distance is shorter in smaller curves.

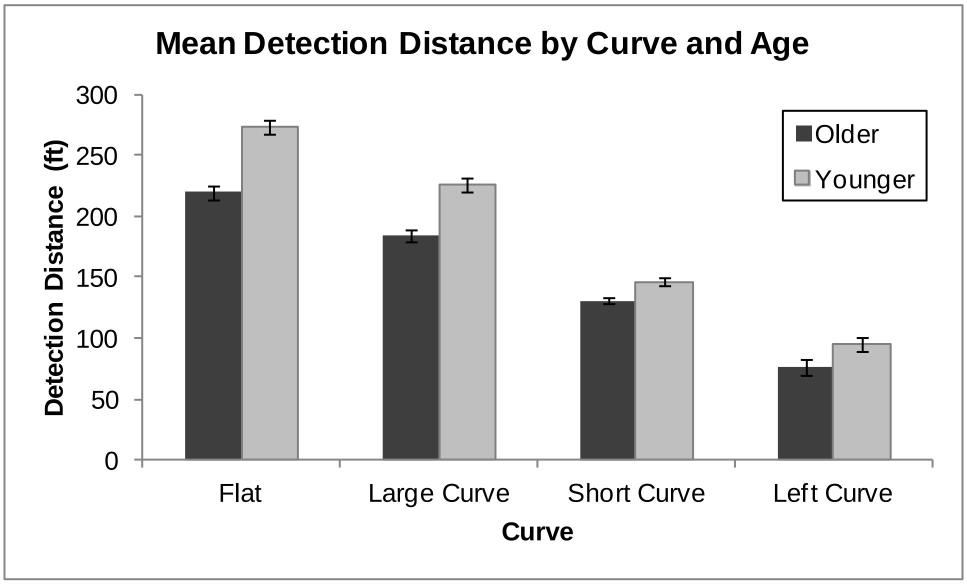


Figure 29. Mean detection distance by curve and age.

A significant interaction was found between headlamp and object. Figure 30 shows that the mean detection distance for targets was significantly higher than that of pedestrians for every headlamp except the HHBs. No difference was found between targets and pedestrians for that headlamp.

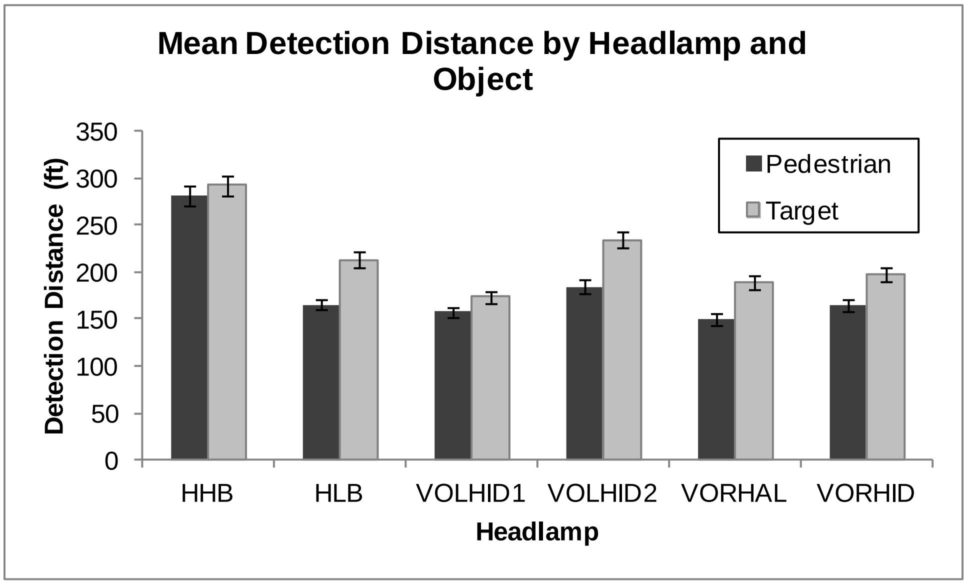


Figure 30. Mean detection distance by headlamp and object.

Figure 31 shows the significant interaction of headlamp and curve. The mean detection distance for the flat roadway was significantly longer than for any of the sag curves for every headlamp except for the HHB. For this headlamp – the only high beam lamp – no significant difference was found between the flat roadway and the large curve. In addition, the mean detection distance for the short curve was significantly longer than that for the left curve for every headlamp except the VORHAL. For this headlamp, no significant difference was found between the short curve and left curve. Among the low beam headlamps, the two VOL headlamps had the longest mean detection distances, and the two VOR headlamps had the shortest detection distances in short curves. This is likely due to the difference in light cutoff on the right side of the beam pattern. VOR headlamps have a horizontal cutoff of the headlight on the right side of the beam pattern, where none exists for the HLB and VOL headlamps. In the left curve, there was little difference among headlamps.

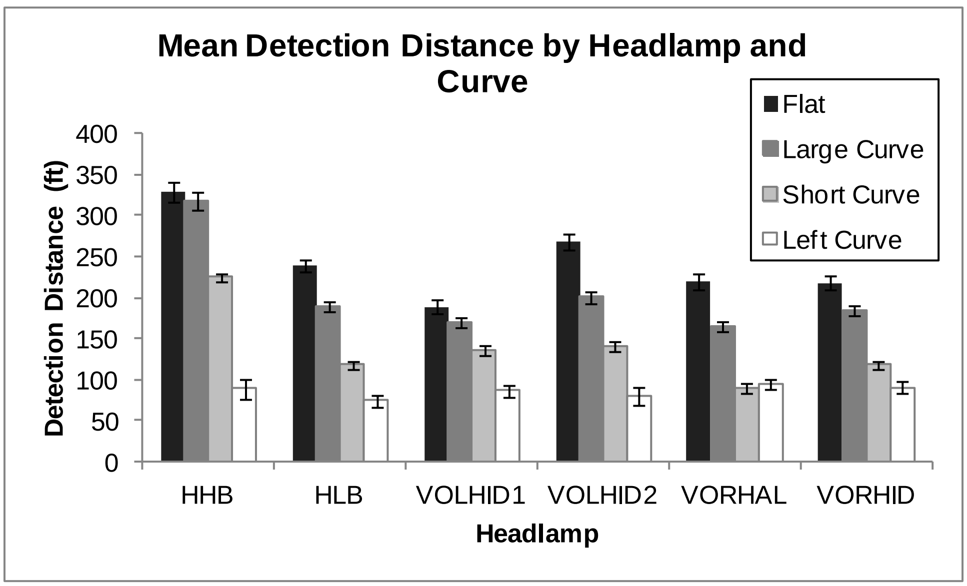


Figure 31. Mean detection distance by headlamp and curve.

A significant interaction was also found between object and curve. No significant difference was found between the mean detection distances for pedestrians and targets on the flat area (242 ft and 246 ft, respectively). In the large curve, however, the mean detection distance for pedestrians (222 ft) was significantly longer than that for targets (186 ft). The reason for this is not immediately clear, but looking at the next significant factor provides some insight.

The three-way interaction of curve, headlamp, and object was found to be significant (Figure 32). For the flat area, there was a significant difference between pedestrians and targets for only one headlamp; the HLBs. In the large curve, the mean detection distance for pedestrians was significantly longer for the HHB, HLB, VOLHID1, and VORHID headlamps. However, the greatest difference was for the HHBs. This is likely because the HHB headlamps produce much more uplight than any of the other headlamps. This number is likely responsible for causing the significant difference that was found for the object and curve interaction. In addition, the mean detection distance for pedestrians with the HHB headlamps was significantly higher in the large curve than in the flat area. This is likely due to the fact that, in the curve, the pedestrian was viewed with a high contrast background (the opposite side of the curved road), whereas the pedestrian had a low contrast background when viewed on the flat road (sky).

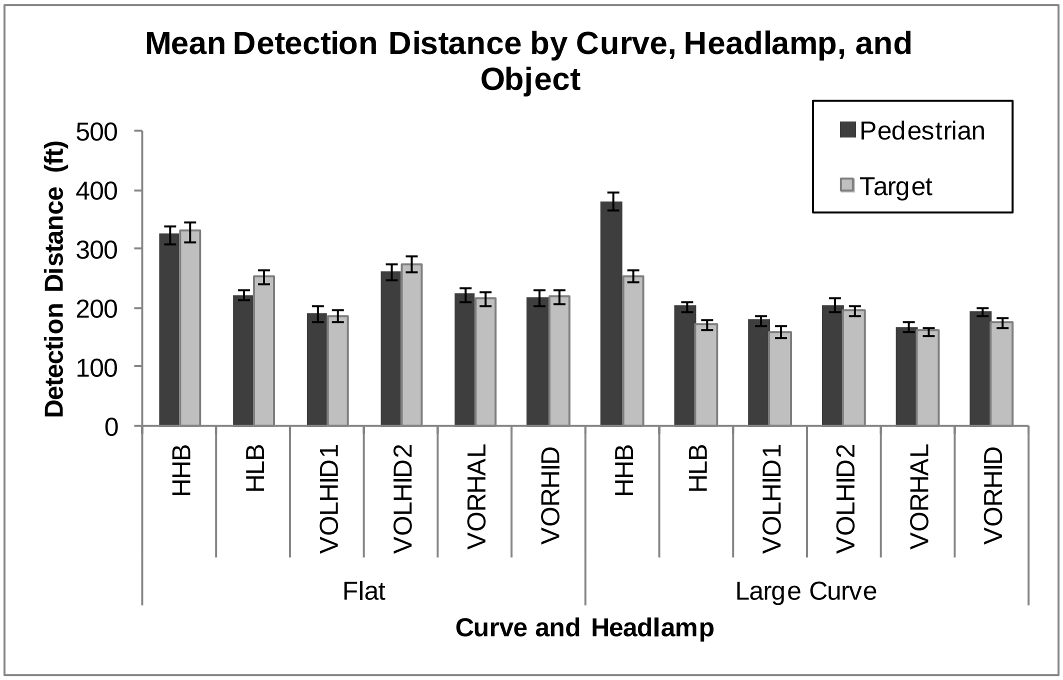


Figure 32. Mean detection distance by curve, headlamp, and object.

Analysis of Headlamp Light Sources and Beam Patterns

Additional analyses were done in order to test for significant effects of light source and beam pattern. While there were no significant main effects of either variable, Table 31 shows the ANCOVA results for the significant interactions of light source and curve, and beam pattern and curve.

Table 31. ANCOVA Results for the Interaction of Light Source and Curve, and Beam Pattern and Curve

Source	DF	Type III SS	Mean Square	F Value	Pr > F	Sig
Light Source*Curve	3	32182.505	10727.502	7.9	0.0001	*
Beam Pattern*Curve	6	36440.787	6073.4646	4.04	0.0009	*

Figure 33 shows that a significant difference between halogen and HID headlamps was only found for the short curve, in which the HID headlamps had a significantly longer mean detection distance. No reason for this effect was immediately apparent, though it was believed that the headlamp beam pattern may have been a confounding variable. The halogen group consisted of one standard-beam headlamp and one VOR headlamp, whereas the HID group consisted of two VOL headlamps and one VOR headlamp. Referring back to Figure 31 in the headlamp analysis, the two VOL headlamps were shown to have the highest mean detection distances in the short curve, other than the HHBs. This led the research team to conclude that the significant interaction found here for light source was most likely due to a confounding effect of beam pattern.

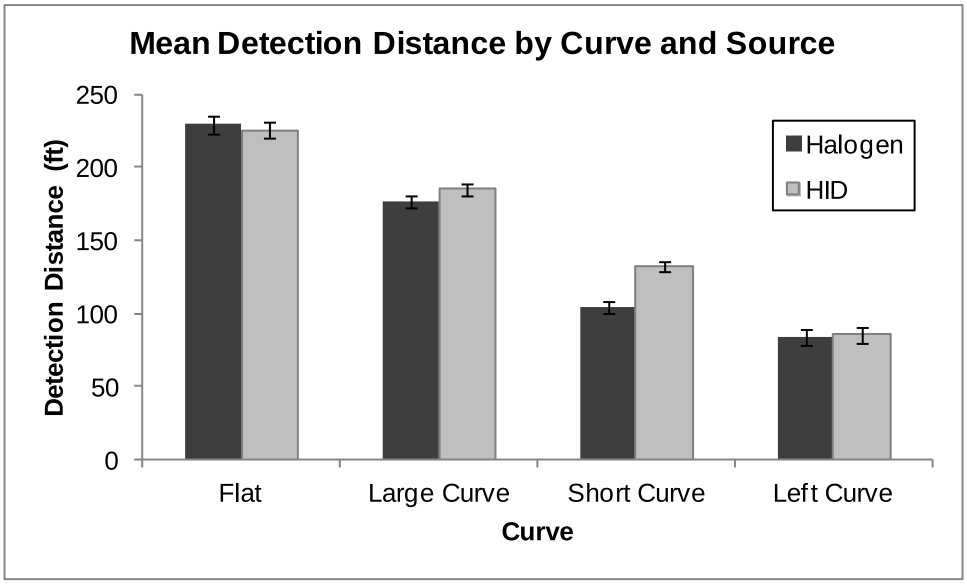


Figure 33. Mean detection distance by curve and source.

Figure 34 shows the significant interaction of beam pattern and curve. A significant difference between the standard-beam pattern and the VOL pattern was only found in the short curve, in which the VOL headlamps had a significantly higher mean detection distance. This is likely due to the increased uplight on the right side of the VOL beam pattern. In the short curve, the relative position of the pedestrian to the vehicle's headlamps likely was high enough in the beam pattern to be out of the standard-beam's hot spot. The standard-beam pattern had significantly longer mean detection distances than did the VOR headlamps in all conditions except in the left curve. This is likely due to a wider hot spot for the VOR headlamps, which reaches further to the left than that of the standard-beam pattern. The VOL headlamps had significantly longer distances than did the VOR headlamps in the large and short curves, but no difference was found in the flat area or left curve. The advantage of the VOL headlamps' uplight was likely negated in these situations, where the VOR's light was able to reach further down the road in spite of its horizontal cutoff in the flat area, and where the pedestrian was detected using the left side of the beam pattern in the left curve. Figure 35 shows a comparison of three of the headlamps as examples of the differences among the beam patterns.

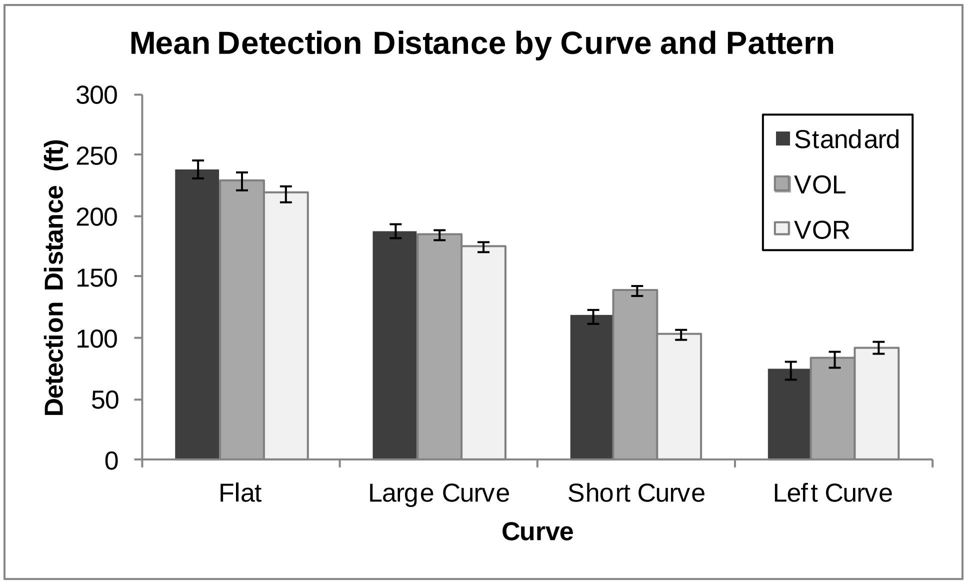


Figure 34. Mean detection distance by curve and pattern.

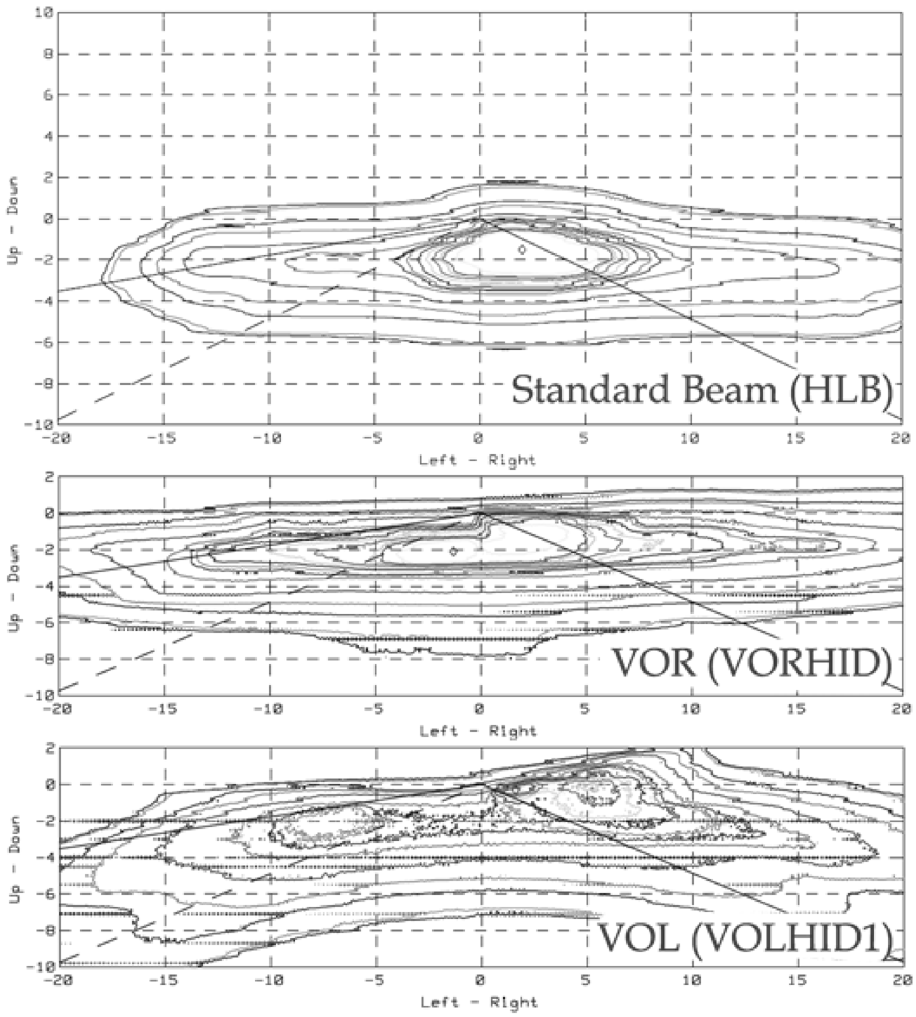


Figure 35. Comparison of beam patterns.

A separate set of analyses was performed for the detection of speed limit signs, which only appeared on the flat roadway. The only significant factor for all three analyses was age. Younger participants were able to read the signs at a distance of about 395 ft, which was significantly further than the average for older participants (which was approximately 267 ft). The headlamp, light source, and beam pattern had no significant effect on the ability to read speed limit signs.

Smart Road Study Discussion

The results of this study indicate that beam pattern is an important indicator of visibility in sag vertical curves. It was expected that modern beam patterns (VOL and VOR) would perform worse than a standard-beam pattern in sag vertical curves due to the increased control of uplight, and stricter cutoffs. While the VOR headlamps did perform worse in the flat roadway, the large curve, and short curve, they actually had significantly better performance in the left curve. In addition, the VOL headlamps were found to have no significant difference from the standard headlamp in most conditions, and actually performed better in one (the short curve). Figure 36 shows the change in mean detection distance for the VOL and VOR headlamps as compared to the standard-beam headlamp. These results indicate that a VOL headlamp may actually provide as good or better visibility across all conditions than either a standard beam or VOR headlamp.

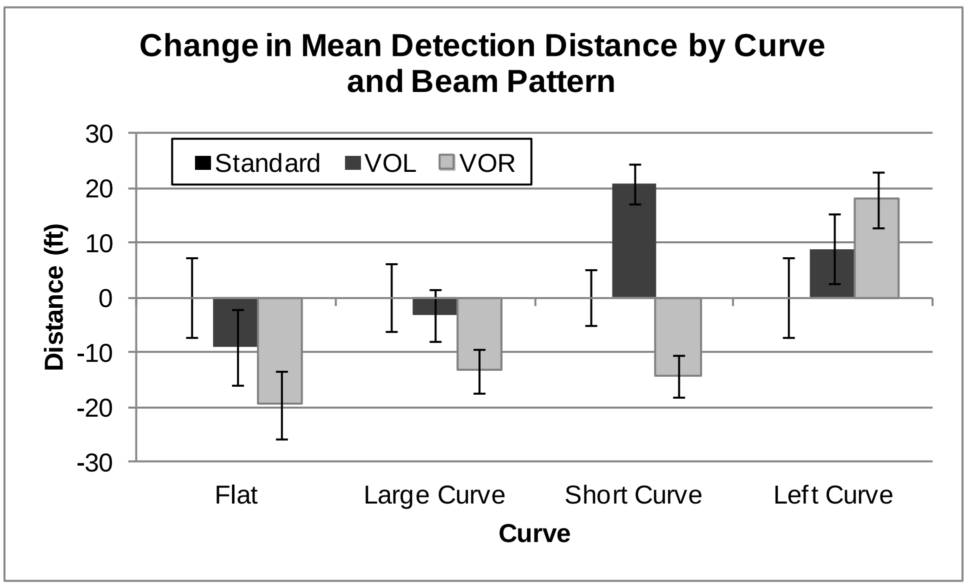


Figure 36. Change in mean detection distance by curve and beam pattern.

Additionally, the differences among beam patterns seem to manifest most strongly in the short curve. However, the VOL headlamps may have had an advantage due to the positioning of the pedestrians in this study. Pedestrians and targets always appeared on the right shoulder of the road which would place them within the portion of the VOL beam pattern which has the most uplight. For objects placed in the roadway, or to the left of the vehicle, the VOL might be found to perform similarly to the other beam patterns.

Because beam pattern seemed to be the most important factor for determining visibility in sag curves, one VOL headlamp and one VOR headlamp were selected for use in the follow-up

Public Road study. Specifically the VOLHID2 and VORHID headlamps were selected so that a direct comparison of beam pattern could be made without the potential confound of light source.

PUBLIC ROAD EXPERIMENTAL DESIGN

The second phase of the experiment took place on public roads in Blacksburg and Christiansburg, VA, and compared VOL and VOR headlamps across 11 sag vertical curves of varying sizes. The study used a 2 (Headlamp) x 12 (Sag Vertical Curve) full-factorial design.

Independent Variables

Several independent variables were manipulated or controlled for this experiment. They are listed below.

Between-Subjects Variables

- Gender (2 levels): Female, Male. The gender independent variable was chosen in order to generalize the results of this study to a broad user population. This factor was used for balance only; it was not used in the data analysis.
- Age (2 levels): Younger (21-34), Older (65+). The younger and older age groups were selected to investigate the changes in vision and perception that may occur with increasing age.

Within-Subjects Variables

- Headlamp (2 levels): VOL, VOR. The two sets of headlamps were chosen in order to compare the performance of the two low-glare beam patterns in sag vertical curves.
- Sag Vertical Curve (12 levels): Eleven sag vertical curves and two flat areas were utilized for the study, creating 12 different levels. Sag vertical curves were given a designation based on which road they were on, which is described in more detail in the Facilities and Equipment section below. The sag curves selected encompass many different lengths across three roadway types (divided highway, two-lane highway, and residential).

Dependent Variables

Detection Distance

The distance at which a participant could identify a target was recorded as a measure of visibility for each curve and flat area. Participants were instructed to verbally identify targets as they drove by saying the word “target.” At that moment, an in-vehicle experimenter would flag the data with a button press. When the vehicle reached the target, the in-vehicle experimenter would again flag the data with a button press. Later analysis determined the distance traveled between these two points, and this was termed the “detection distance.” Figure 37 illustrates the two points at which the data was flagged.

Detection distance as defined in this report may be more closely related to recognition distance in that participants had to identify what an object was, rather than simply detect that *something* was there. However, as there was only one object used in this study, it is likely that detection and recognition were nearly simultaneous.

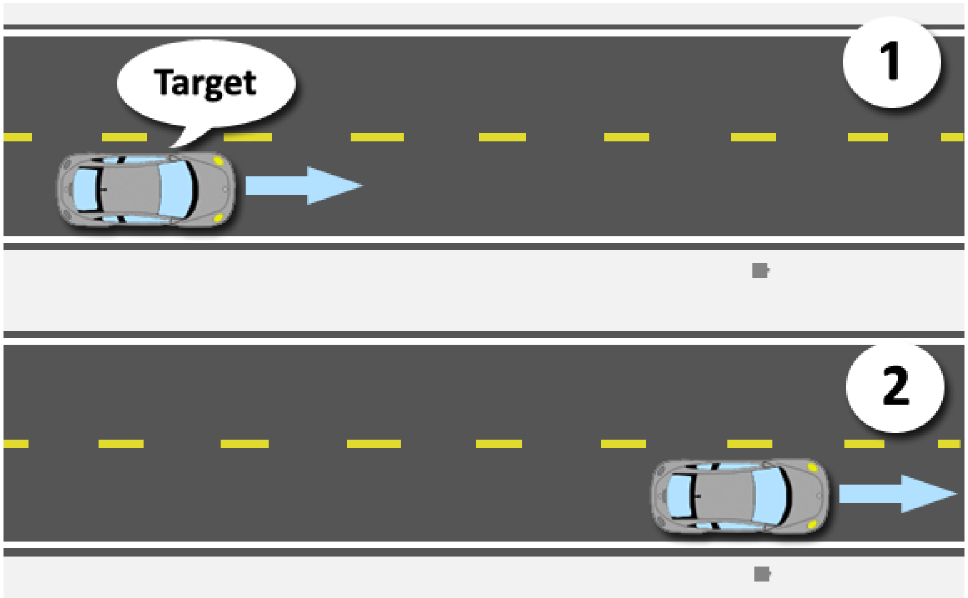


Figure 37. Determining detection distance.

Participants

Twenty-four participants were selected to take part in this study. Participants were selected from two age categories: younger (18-34 years old) and older (65+). Six younger males, six older males, six younger females, and six older females participated. Recruitment occurred through the VTTI participant database and word-of-mouth. A general description of the study was provided to the subjects over the phone before they decided if they were willing to participate. If they were interested, subjects were then screened with a verbal questionnaire to determine whether they were licensed drivers and whether they had any health concerns that should exclude them from participating in the study. If subjects were determined to be eligible for the study, they were then scheduled to come to VTTI for participation. When subjects arrived at VTTI, they read and signed an informed consent form. Subjects were paid $20/hr and were allowed to withdraw at any point in time, with compensation adjusted accordingly.

Participants' Age and Visual Capabilities

Younger participants' ages ranged from 21 to 32 years old, with a median age of 23 years. Older participants' ages ranged from 65 to 69 years old, with a median age of 67 years. One participant failed a color-blindness test. All other participants passed, with only two participants giving a single incorrect response each. Table 32 presents the distribution of visual acuity scores. A minimum of 20/40 was required for participation. Participants were allowed to wear corrective lenses if they indicated that they normally wear them while driving.

Table 32. Visual Acuity Scores

Visual Acuity (Snellen)	Number of Participants
20/13	4
20/15	3
20/20	8
20/25	5
20/30	3
20/40	1

Participants' visual acuity was also measured in the presence of glare using a BAT. The distribution of visual acuity scores for each eye and level of glare are presented in Table 33.

Table 33. Visual Acuity in the Presence of Glare

	No Glare		Low Glare		Med Glare		High Glare	
Acuity Score	**Left Eye**	**Right Eye**	**Left Eye**	**Right Eye**	**Left Eye**	**Right Eye**	**Left Eye**	**Right Eye**
20/13	2	3	3	2	1	1	1	1
20/15	3	2	1	1	2	1	0	0
20/20	7	5	3	6	5	6	3	4
20/25	6	6	8	6	5	5	5	4
20/30	2	5	5	3	5	5	5	5
20/40	2	1	1	5	3	1	5	5
20/50	1	2	1	0	1	3	4	2
20/60 and worse	1	0	2	1	2	2	1	3

Facilities and Equipment

Test Route

This experiment was conducted on public roads in Blacksburg and Christiansburg, VA. The route encompassed 11 sag vertical curves on three types of roadways: divided highway (four curves), two-lane highway (five curves), and residential (two curves). Figure 38 shows a map of the route. Participants departed from VTTI, drove to a cul-de-sac in a residential neighborhood where they turned around, and then drove to the end of the route marked by the number 3 on the map. At this point participants switched vehicles, and returned to VTTI driving the same route in the opposite direction.

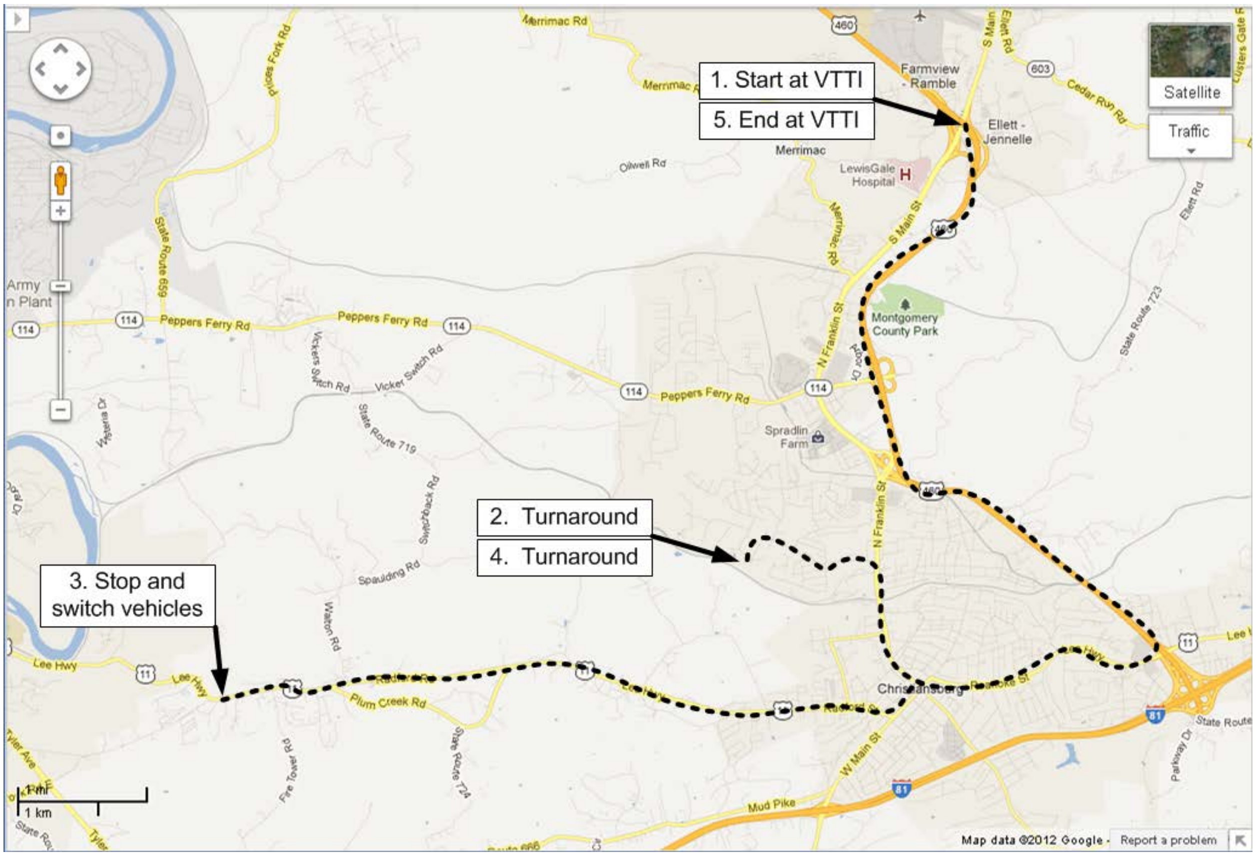


Figure 38. Test route (Source: Google).

Measurements of a majority of the sag vertical curves were found using the design documents which were supplied by the Virginia Department of Transportation (VDOT). In cases where the design documents were unavailable, measurements were made using GPS data recorded using a GPS-enabled vehicle. The data were processed in ArcGIS™ and ArcMap™ 10 software to generate the elevation, giving a profile of the curves. The tangent lines were found visually using a straight edge. The slopes of the tangent lines were calculated to determine the algebraic change in grade while the horizontal distance between the tangent points was used to determine the length of the curves. Table 34 summarizes the curve information. It also shows the minimum K value based on design speed, and the actual K value – called K reality or K_r – based on the design documents or the grade and length measurements. Shaded cells indicate curves which were not designed to the AASHTO criteria. Radford Road was designed in 1940, before the first AASHTO Green Guide was issued. Route 460 was designed in 1965 after the AASHTO guide was introduced, but the mountainous terrain may have prevented designing to these standards.

Table 34. Sag Vertical Curve Measurements

Road Name	**Road Type**	**Design Speed (mph)**	**Minimum K**	**Algebraic Change in Grade, *A* (%)**	**Length, *L* (ft)**	**K_R (*L/A*)**
Route 460 East	Divided Highway	60	136	4.73	600	127
Route 460 East	Divided Highway	60	136	12.00	800	67
Route 460 West	Divided Highway	60	136	4.28	600	140
Route 460 West	Divided Highway	60	136	12.00	800	67
Independence Blvd*	Residential	25	26	18.75	500	27
Radford Rd	Two-lane Highway	45	79	10.00	500	50
Radford Rd	Two-lane Highway	45	79	6.00	500	83
Radford Rd	Two-lane Highway	45	79	5.90	500	85
Radford Rd	Two-lane Highway	45	79	4.14	500	121
Radford Rd	Two-lane Highway	45	79	9.22	500	54
Sapphire Ave*	Residential	25	26	19.17	320	17

* Measurements for these curves were made by the research team as the design documents were unavailable.

Headlamps and Test Vehicles

Participants drove a 1999 and 2000 model Ford Explorer, each equipped with a different set of headlamps. The headlamps used in the study are summarized in Table 35 below. These headlamps were selected to investigate the effect of beam pattern on visibility in sag vertical curves.

Table 35. Headlamps

Headlamp Abbreviation	Description	Original Vehicle	Photo
VOL	Visually Optically Aligned Left HID	Mercedes E320	
VOR	Visually Optically Aligned Right HID	Lincoln Navigator	

The test vehicles were also equipped with DASs. The DAS recorded video both inside and outside of the vehicle and button inputs from the in-vehicle experimenter, as well as network data such as speed and distance. Detection distance was determined by analysis of this data.

Public Road Experimental Method

Participants were initially contacted and screened on the phone using an internal VTTI database of persons who had expressed interest in participating in research studies. When participants arrived at VTTI for participation, they first read and signed the informed consent. Participants then filled out a W9 tax form, and a health history questionnaire. These were followed by vision tests for acuity, contrast sensitivity, and color blindness. Participants were only excluded from participation if visual acuity was less than 20/40 (the legal minimum to hold a Virginia driver's license), or if they had taken any substance which might impair their ability to drive.

Participants were scheduled in pairs. Once the paperwork and vision tests were complete, an in-vehicle experimenter explained the instructions for the study and answered any questions the participants had. The participants were then escorted to their assigned vehicle by an in-vehicle experimenter. The participant in the first vehicle was instructed to begin driving the route, while the second participant waited approximately 60 seconds before beginning the drive. This kept the two vehicles apart during the drive so that one would not interfere with the other. Participants were given turn-by-turn directions by the in-vehicle experimenter so that they did not have to memorize the route. At the end of the route, participants were instructed to stop in a parking lot. Here, the participants switched vehicles before retracing the route back to VTTI.

As participants drove, they would verbally identify the targets as they encountered them. Targets always appeared on the driver's right hand side. In addition to identifying targets, participants read aloud the number on any speed limit sign they encountered as soon as they could read it. This task was used only to keep participants active and alert during long stretches between sag vertical curves. The point at which participants identified a target was flagged in the data by the in-vehicle experimenter by pressing a button. The moment at which the vehicle reached the target was also flagged by another button press.

Once participants had completed the route and returned to VTTI they were paid for their participation, and given a receipt and a copy of the informed consent. Participants were compensated at a rate of $20 per hour.

Presentation Orders

Because all participants drove the same route, the presentation order of the sag vertical curves was fixed. The order of the headlamps was balanced with half of the participants using VOL headlamps first, followed by the VOR headlamps, and the other half of participants using VOR headlamps first, followed by the VOL headlamps. Table 36 shows which curves were seen with which headlamps for a pair of participants. Directions 1 and 2 refer to the first and second half of the route. All participants saw the curves in the residential area (IND and SAP) in both directions with both headlamps.

Table 36. Headlamp Presentation Orders

	Participant 1		**Participant 2**	
Curve	**Direction 1**	**Direction 2**	**Direction 1**	**Direction 2**
460E1	VOL		VOR	
460E2	VOL		VOR	
IND	VOL/VOR	VOL/VOR	VOL/VOR	VOL/VOR
SAP	VOL/VOR	VOL/VOR	VOL/VOR	VOL/VOR
RAD1	VOL	VOR	VOR	VOL
RAD2	VOL	VOR	VOR	VOL
RAD3	VOL	VOR	VOR	VOL
RAD4	VOL		VOR	
RAD5		VOR		VOL
Flat	VOL	VOR	VOR	VOL
460W1		VOR		VOL
460W2		VOR		VOL

Public Road Data Analysis

An ANCOVA with a significance level of 95% (α = 0.05) was used. Because the speed limits on the sag vertical curves varied, and speed may have an impact on object detection, vehicle speed was used as the covariate.

PUBLIC ROAD STUDY RESULTS

Table 37 shows the ANCOVA results for the detection of targets. No factors were found to be significant.

Table 37. ANCOVA Results for the Headlamp Analysis

Source	DF	Type III SS	Mean Square	F Value	Pr > F	Sig
Age	1	2940.6471	2940.6471	0.27	0.6108	
Headlamp	1	11246.658	11246.658	3.51	0.0766	
Age*Headlamp	1	159.81033	159.81033	0.05	0.8257	
Curve	11	53046.425	4822.4023	1.73	0.0683	
Age*Curve	11	41229.965	3748.1787	1.35	0.2006	
Headlamp*Curve	5	13482.899	2696.5798	1.58	0.1772	
Age*Headlamp*Curve	5	5007.1958	1001.4392	0.59	0.7099	
Total	35	127113.6				
* $p < 0.05$ *(significant)*						

While no factors were found to be significant, headlamp and curve both had relatively low p values. (0.07 and 0.06, respectively). For the headlamp factor, the VOL headlamps had a mean detection distance of 91ft compared to 78 ft for the VOR headlamps. This is a small difference, but it does appear that the VOL headlamps provide slightly better visibility than VOR headlamps, at least for objects on the right side of the vehicle.

While curve was not found to be significant, SNK pairwise comparisons show that there were significant differences between curves. Figure 39 shows the mean detection distance for each curve as well as the flat area. Some curves had longer mean detection distances than the flat area, and even though they were not significantly different, it seems counterintuitive. A possible factor in this may have been the presence of other vehicles. The section of Route 460 used in the study is a particularly busy section, and it is possible that the headlights from a leading vehicle illuminated the targets for a participant. Another interesting result is that the two curves on Route 460 Westbound had significantly higher detection distances than the virtually identical curves on Route 460 Eastbound. This is likely the result of an order effect. The two targets on the eastbound lanes were the first that participants encountered, and the two targets on the westbound lanes were the last two that participants encountered. It is likely that participants improved at detecting targets as the night went on. That is to say that they became more aware of what they should be looking for, and where the targets might appear.

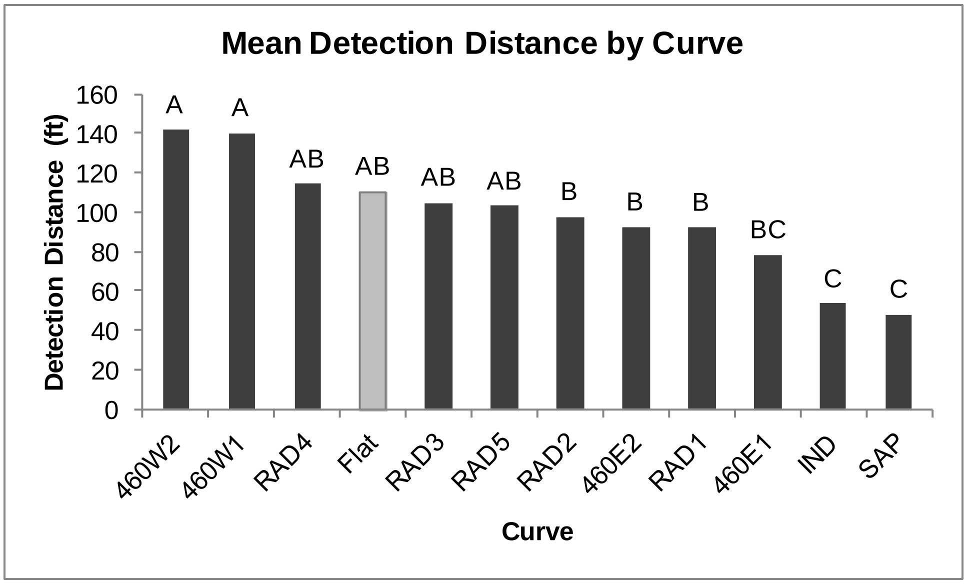


Figure 39. Mean detection distance by curve.

Public Road Study Discussion

Interestingly, only the two curves in the residential neighborhood (IND and SAP) had a mean detection distance that was significantly shorter than the flat area. All other curves were not statistically different from the flat detection distance. The reason that the two residential curves were the only curves to have significantly shorter detection distances than the flat roadway was not immediately apparent. One direction of the Sapphire Avenue curve (SAP) had a crest vertical curve just prior to the sag curve which blocked the view of the target at a certain distance, but this did not appear to be an issue because the standard deviation for that curve was quite small (5.25 ft for VOL headlamps, and 2.5 ft for VOR headlamps). The mean detection distance for each curve was plotted against each measured aspect of the curve (length, change in grade, K_R) to determine if a relationship could be found to explain at what point a curve's mean detection distance could become diminished as compared to flat detection.

Figure 40 shows the mean detection distance by curve length, with the two residential curves (IND and SAP) indicated by the two white squares. The figure also shows the linear trend line with the associated R^2 value. While the shortest curve did have the lowest mean detection distance, there is only a weak relationship between detection distance and curve length. There were numerous curves with lengths similar to the IND curve which were not significantly different from the flat roadway. Thus, the point at which a curve's detection distance becomes significantly less than flat roadway cannot be explained solely by curve length.

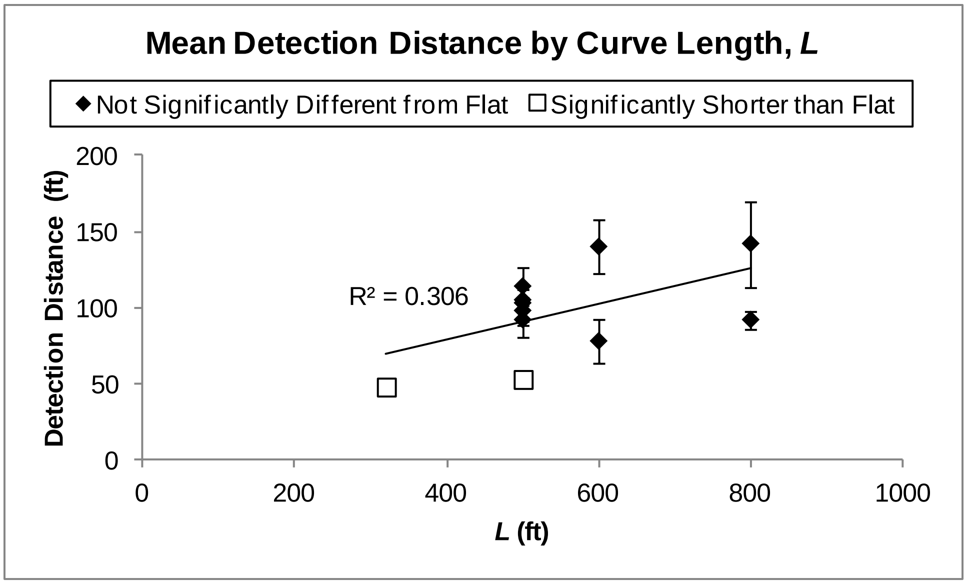


Figure 40. Mean detection distance by curve length.

Figure 41 shows the mean detection distance by the algebraic change in grade for each curve, along with the linear trend line and associated R^2 value. There is a weak negative correlation between *A* and detection distance, and the two residential curves which had significantly shorter mean detection distances than the flat roadway are shown to have the largest values for *A* by far. This may indicate that the point at which a curve's detection distance becomes less than flat roadway may be when that curve's algebraic change in grade is somewhere between 13% and 18%.

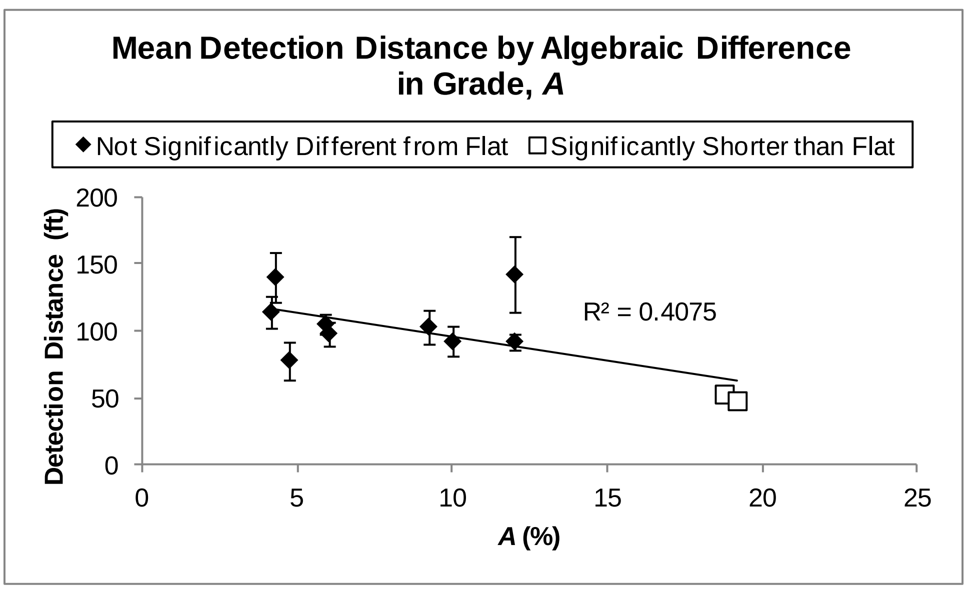


Figure 41. Mean detection distance by algebraic change in grade.

Finally, Figure 42 shows the relationship between detection distance and the rate of curvature, K_R, as well as the linear trend line and associated R^2 value. A weak positive correlation was found where a larger K value tends to result in longer detection distances. The two residential curves which had mean detection distances which were significantly shorter than flat roadway had the lowest K_R values. Thus, the point at which a curve's detection distance becomes less than flat roadway may be somewhere between K_R values of 27 and 50.

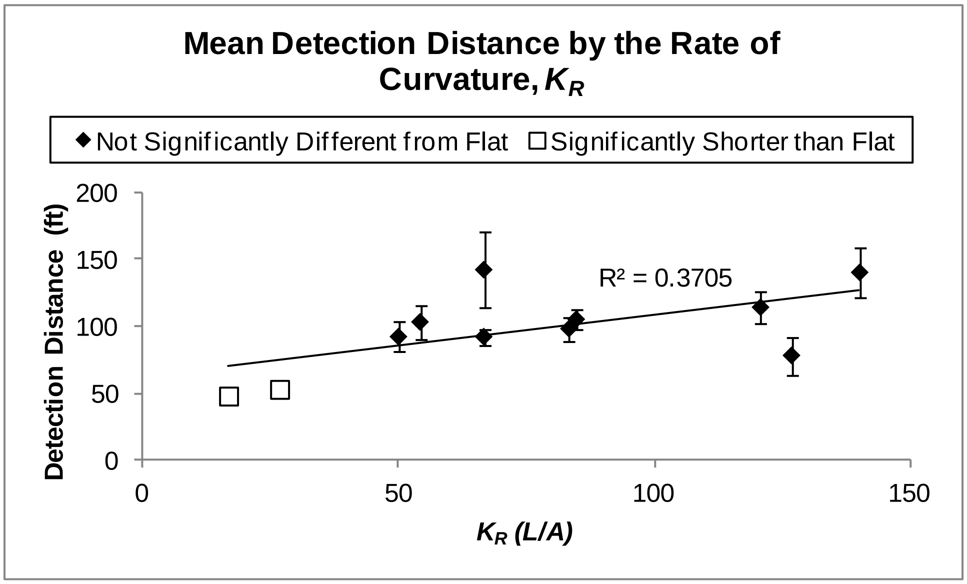


Figure 42. Mean detection distance by K_R.

A much stronger relationship between K_R and detection distance was expected. However, while the relationships between detection distance and the various curve measures were weak, there did appear to be some thresholds for the change in grade, *A*, and rate of curvature, K_R, that might explain which curves will have reduced visibility as compared to flat roadway. Unfortunately, those thresholds could not be pinpointed within this data. Further research could attempt to validate these findings, and narrow the window by examining visibility in curves with a wide range of *A* and K_R values.

CHAPTER 7 DISCUSSION ON AASHTO GUIDELINES

The potential changes to the AASHTO policy on the design of sag vertical curves discussed in Chapter 5 – a result of the literature review and survey – must be reconsidered with the additional data from the visibility experiments. A review of each solution follows.

Solution 1: Extend Sag Curve Length

The initial argument for extending the length of the curve came from the assumption that the headlight SD is shortened by the terrain. The results of the visibility experiments suggest that this may not be the case, however. In the Public Road study, the majority of curves provided detection distances that were not significantly different from the flat roadway. Decreased SD with respect to a flat roadway only occurred in the two residential curves, with design speeds of 25 mph. While lengthening these curves may provide a benefit, the mean detection distance for a target on flat roadway was found to be 110 ft in the Public Road study, and 230 ft in the Smart Road study (excluding high beam headlamps). Even using the longer of the two distances, the detection distance is still 20 ft shorter than the SSD for a 35 mph design speed. This suggests that even if the curves were completely flattened, the detection distance of an object may still only satisfy the SSD of a 30 mph design speed or less.

In the Public Road study, participants only identified small targets which were approximately 7 inches (178 mm) square, while the Green Book (AASHTO, 2004) assumes an object height of 2 ft (600 mm). It was believed this difference may have accounted for at least some of the discrepancy between detection distance and SSD. However, in the Smart Road study, the mean detection distance for a pedestrian – a considerably larger object – was 224 ft on flat roadway (using low beam headlamps), which was shorter than the mean detection distance for a target under the same conditions (230 ft). A study conducted by Fambro, Fitzpatrick, and Koppa (1997) found a similar result, with participants able to detect a pedestrian using low beam headlamps at approximately 250 ft. Another study by Wood, Tyrrell, and Carberry (2002) found a mean detection distance of 251 ft for pedestrians using low beam headlamps. However, this mean distance included pedestrians wearing reflective vests and biomotion reflectors. Figure 43 shows the response distance by clothing and age for the low beam headlamps. As shown, the response distance for pedestrians not wearing reflective materials was much shorter.

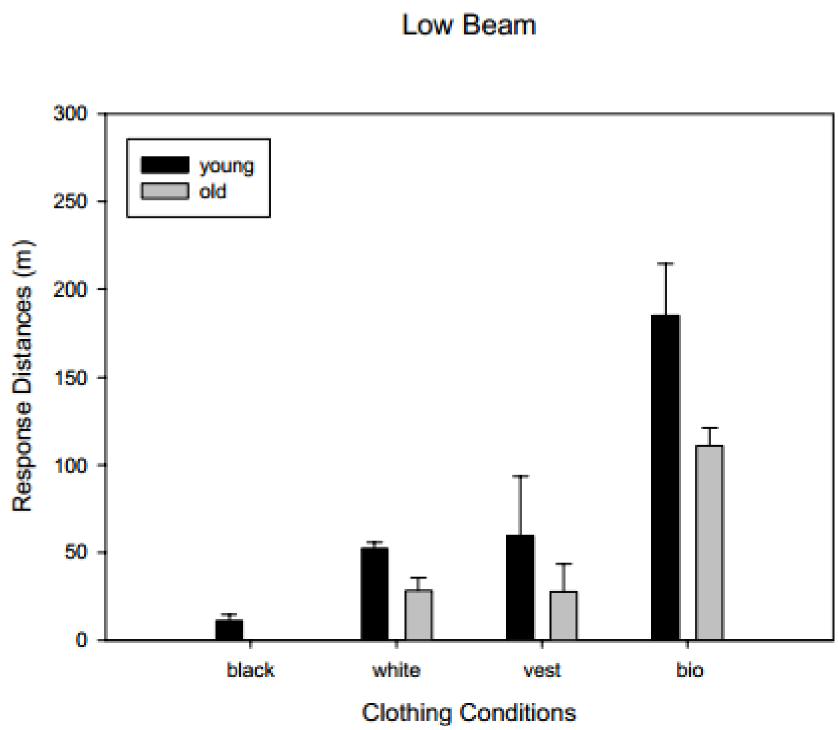


Figure 43. Mean detection distance for pedestrians by clothing and age (Source: Wood, Tyrrell, & Carberry, 2002).

This data suggests that extending the length of a sag vertical curve may provide a benefit for curves with design speeds less than 30 mph. For curves with design speeds greater than 30 mph, extending the length will provide no benefit as the visibility distance provided by the headlamps will be the limiting factor.

Solution 2: Increase Deceleration Rate

The second suggested solution was to increase the deceleration rate to a value which more closely matches the braking patterns of a typical driver. AASHTO defines the SSD as:

$$d = 1.47Vt + 1.075\frac{V^2}{a} \tag{9}$$

Where t is brake reaction time in seconds, V is the design speed in mph, and a is the deceleration rate in ft/s^2. According to AASHTO, the current SSD assumes that: 1) the reaction time is 2.5 s, and 2), the deceleration rate is 11.2 ft/s^2 (AASHTO, 2004). If we consider the detection of a target on flat roadway from the Smart Road study (which had the highest mean distance found in the visibility experiments), we can plug in the detection distance for d, and determine what deceleration rate would be needed to stop in this distance, which was 230 ft. Transforming the equation to solve for a, we find that:

$$a = \frac{1.075V^2}{d - 1.47Vt} \tag{10}$$

Using AASHTO's values for brake reaction time, and a visibility distance of 230 ft, we find the deceleration rates required to stop in that distance by design speed. Table 38 shows these results. The standard deceleration rate of 11.2 ft/s^2 would need to be increased beginning at a design speed of 35 mph, and increasing exponentially from there to unrealistic values. At a design speed of 65 mph, the distance traveled during the braking reaction time has already exceeded the 230 ft distance, which was the highest mean detection distance found.

Table 38. Needed Deceleration for a Visibility Distance of 230 ft

Design Speed (mph)	Deceleration Rate (ft/s^2)
15	1.38
20	2.75
25	4.86
30	8.08
35	12.99
40	20.72
45	$> g$
50	$> g$
55	$> g$
60	$> g$
65	$> g$
70	$> g$
75	$> g$
80	$> g$

* $g = 32 ft/s^2$

Based on the detection distances found in the visibility experiments, increasing the deceleration rate would not be a practical way to bring SSD closer to headlight SD. Using the best case scenario of viewing a target on flat roadway, increasing the deceleration rate would only be feasible at one design speed (35 mph). Any speeds greater than that would require excessive or impossible rates of deceleration.

Solution 3: Decrease Design Speed

As already demonstrated, the best case scenario for object detection was for a target on flat roadway, with a detection distance of 230 ft. If we assume that this is the maximum distance for object detection using low beam headlamps, a design speed of less than 35 mph would be required in order for SSD to fall within this range. It would be impractical to decrease the design speed for a sag vertical curve from 55 mph to 30 mph, for example. Even if such a method were used, this would not address the fact that the headlight SD would still fall short of SSD for every other part of the roadway for any design speed greater than 30 mph.

Discussion of the Appropriateness of SSD

The AASHTO design requirements for sag vertical curves are based on four factors: headlight SD, passenger comfort, drainage control, and general appearance. The headlight SD is typically the primary factor, however, because: 1) it requires a minimum rate of curvature which is higher than the minimum required for passenger comfort, 2) drainage control is a maximum rate of curvature which is not often approached, and 3) the general appearance criteria is of lower priority, and is often satisfied by meeting the headlight SD requirements.

The original intent of this project was to determine how modern headlamps impact headlight SD, since the calculations for SSD are based on older sealed-beam headlamps. It was discovered that standard-beam headlamps do provide significantly longer detection distances than that of VOR headlamps in most conditions, but the same is not true for VOL headlamps. VOL headlamps performed similarly or sometimes better than the standard beams in each of the conditions tested (refer to Figure 33 and Figure 35). More importantly, however, it was discovered that all headlamps - including the standard-beam headlamps - were not able to provide mean detection distances that met requirements for SSD in most conditions. So while there were some differences among the different beam patterns, the larger issue became that the assumed SD used in the determination of SSD overestimates the actual visibility provided by ALL headlamps – not just modern beam patterns.

At the same time, however, the majority of states which responded to the survey indicated that sag vertical curves are only occasionally or almost never problematic locations. This suggests that even though the SD falls short of SSD in many cases, it still allows enough visibility for generally safe driving. If this is the case, does that mean sag vertical curves are being over-designed for SSD requirements which are not met and not needed?

If we assume that headlight SD is adequate for safety, then a combination of these criteria could be used for the design of sag curves where the design speed determines whether the SSD, SD, or comfort criteria will be used. Figure 44 shows a simplification of the K values for different design speeds based on the SSD and comfort criteria as stated by AASHTO, as well as the calculated K for an SD of 230 ft (which was the longest mean detection distance for flat roadway in the visibility experiments). For speeds less than 35 mph, the SSD is less than the headlight SD. For this range of design speeds, the SSD would be the criterion used, as increasing the curve length to reach headlight SD would provide no benefit. For speeds above 45 mph, the comfort criterion would be used because the headlight SD would also be satisfied within that criterion. For speeds between 35 and 45 mph, the headlight SD would be used because there would be no benefit in designing up to the SSD criterion.

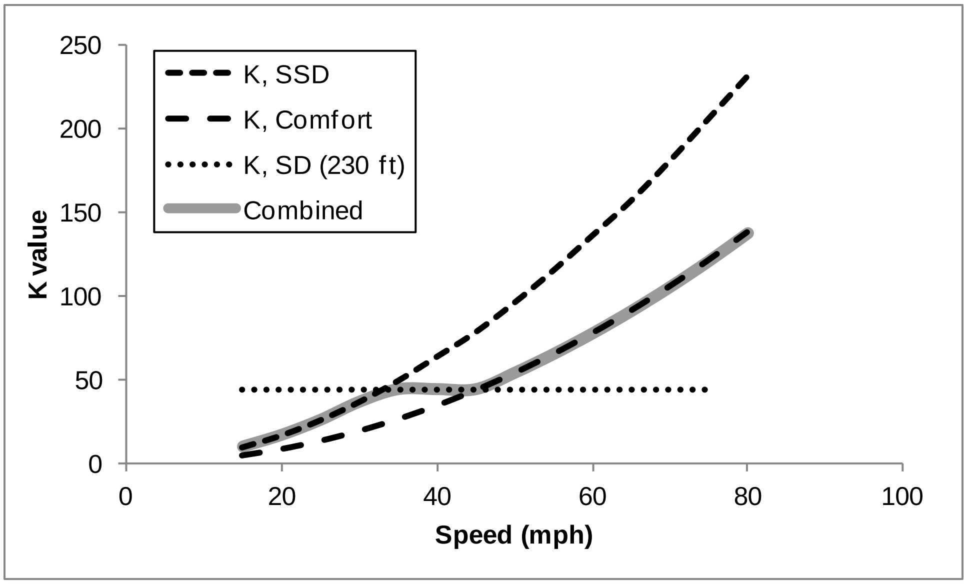


Figure 44. K values for sag vertical curves.

**Please notice that this plot is not valid for very low algebraic differences and very short curves where the stopping sight distance is less than the length of the curve as explained in Chapter 3.

The model illustrated in Figure 44 used the mean detection distance; however, the concept works for other values as well. Roadway designers may wish to design for a longer detection distance, such as the 95th percentile, so as not to handicap drivers who have above average vision. Figure 45 shows how different levels of SD would affect the shape of the combined curve.

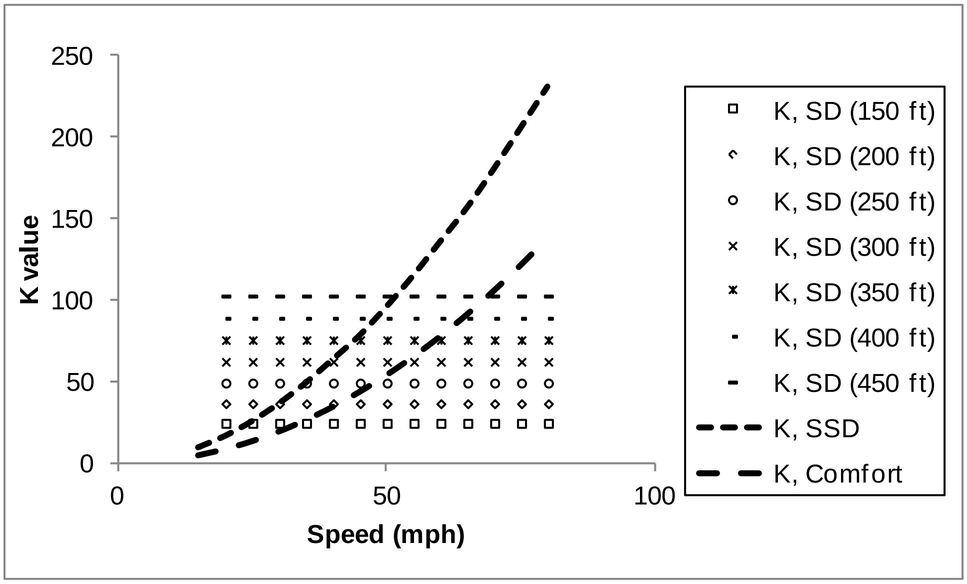


Figure 45. K values for different headlight sight distances.

The benefit of such a design approach would be potential cost savings due to decreased curve lengths. However, this approach is based on the assumption that current visibility distances provided by headlamps are sufficient for safety. Further research is required to test this assertion before any true design alternative could be proposed.

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The research has shown that:

- The distance at which drivers can detect objects in reality falls significantly short of the headlight SD calculations used in determining the design of sag vertical curves.
- Neither changing the length of the curve, the deceleration rate, nor the design speed would be sufficient for increasing the headlight SD.
- The only way to increase headlight SD in order to match SSD would be enhancements to the headlamps or the addition of other vision enhancement systems to supplement the headlamps.

RECOMMENDATIONS

Based on these conclusions, no recommendation for changes to the AASHTO design policy is being proposed at this time. Rather, it is recommended that a significant review of the current values of safe SSDs and headlamp performance be considered to align the performance requirements of the driver and the performance delivered by the headlamps system. This review may include the consideration of the potential changes in the SSD as discussed in this report or changes in headlamp requirements.

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ABBREVIATIONS AND ACRONYMS

2R	Resurfacing and Restoration
3R	Resurfacing, Restoration and Rehabilitation
AADT	Annual average daily traffic
AASHTO	American Association of State Highway and Transportation Officials
ANCOVA	analysis of covariance
BAT	Brightness Acuity Tester
DAS	Data Acquisition System
DOT	Department of Transportation
ECE	Economic Commission for Europe
ENV	Enhanced Night Visibility
FHWA	Federal Highway Administration
FMVSS	Federal Motor Vehicle Safety Standard
GPS	Global Positioning System
GRE	Group Rapporteurs Eclairage
GTB	Groupe de Travail-Bruxelles 1952
HHB	halogen high beam
HID	High-intensity discharge
HLB	halogen low beam
HLB-LP	low-profile halogen low beam
K	rate of vertical curvature
LED	light-emitting diode
mph	miles per hour
RRR	Resurfacing, Restoration and Rehabilitation
SAE	Society of Automotive Engineers

SD	sight distance
SNK	Student-Newman-Keuls grouping
SSD	stopping sight distance
V	speed
VDOT	Virginia Department of Transportation
VOA	visually/optically aimable
VOL	headlamps aimed using the vertical gradient to the left of vertical
VOLHID	visually optically aligned left high-intensity discharge
VOR	headlamps aimed using the vertical gradient to the right of vertical
VORHAL	visually optically aligned right halogen
VORHID	visually optically aligned right high-intensity discharge
VPD	vehicles per day
VPI	Vertical Point of Intersection
VDOT	Virginia Department of Transportation
VTTI	Virginia Tech Transportation Institute

APPENDIX A PRACTITIONER SURVEY

Sag Vertical Curve Design Criteria

Survey Questionnaire for

NCHRP 15-41*Sag Vertical Curve Design Criteria for Headlight Sight Distance*

Thank you very much for participating in the Sag Vertical Curve Design Criteria Survey.

We expect that it should take no more than 15 minutes to complete the survey. The expectation is that most answers will be completed by attaching existing documents. In the absence of such supporting documents, it may take about 30 minutes. Feel free to skip any question. The more important objective of this survey is to collect information regarding agency standards for vertical curves and at a minimum we appreciate if you can provide us with the documentation or an URL site for the sag vertical curve design criteria used by your agency

We are requesting that the completed survey and attachments be returned to us by July 31, 2010 via email to Kelly Stanley, kstanley@vtti.vt.edu.

If you have any question please feel free to contact Alejandra Medina, ale@vtti.vt.edu 540-231-1508, Ron Gibbons at rgibbons@vtti.vt.edu, 540-231- 1581 or Kstanley@vtti.vt.edu, 540-231-1088

If this survey would be better answered by somebody else within your office, please feel free to forward it to that individual.

Thank you in advance for your help and cooperation with this project

General Information

1) Please provide your contact information

Name:	
Current Position/Title:	
Agency:	
Address	
City, State, Zip code:	
Phone:	
Email:	

1. Does your Agency have a documented design criteria for vertical sag curves (Road Design Manual, Design Specifications, etc)?

❍ Yes ❍ No

If your answer is yes, please provide the documentation to this survey or provide us the URL of the site.

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2. Are these criteria the same as the AASHTO "AASHTO ***Policy on Geometric Design of Highways and Streets*****?**

❍ Yes ❍ No

If your answer is no, please provide the explanation documentation that the sag vertical curve design criteria is based on.

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3. Are there any situations where your agency recommends the designer use different specifications than the ones specified on your answer for question 1?

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4. Which criteria do you use when designing Vertical Sag Curves?

- ❍ Headlight sight distance
- ❍ passenger comfort
- ❍ drainage control
- ❍ general appearance
- ❍ sight distance at undercrossings
- ❍ decision or passing sight distance considerations
- ❍ others. Please specify

5. For the headlight sight distance criteria, do you use the same AASHTO criteria of 2 feet for headlight height and a 1 degree upward divergence of the light beam from the longitudinal axis?

❍ Yes ❍ No ❍ Not Sure

If your answer is no please explain

6. If you checked yes for the drainage control criteria, please explain the design criteria used and attach the documentation or provide us with an URL of the site.

7. If you check yes for general appearance please explain what factors or criteria you use to determine the length of the sag vertical curve and attach the documentation.

8. Does your agency have any specifications for the case of sag vertical curves underpassing a structure?

❍ Yes ❍ No

If your answer is yes please provide the documentation or provide us the URL of the site

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9. What are the design criteria for vertical sag curves required by your agency in the case of continuously lighted sections of highway?

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10. Does your agency allow short vertical sag curves in special situations (economic reasons, ramps, etc.)?

❍ Yes ❍ No ❍ Not Sure

If your answer is yes please provide the documentation or provide us the URL of the site

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11. Has your agency identified any issues with the current design criteria for vertical sag curve that need to be addressed?

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12. Has your agency conducted any studies regarding vertical sag curves design or safety?

❍ Yes ❍ No ❍ Not Sure

If your answer is yes please provide the documentation or provide us the URL of the site

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13. Regarding safety and accidents in your jurisdiction are sag vertical curves problematic locations?

❍ Always ❍ Frequently ❍ Occasionally ❍ Almost Never ❍ Never

14. Do your accident records identify accidents occurring vertical sag curves?

❍ Yes ❍ No ❍ Not Sure

Note: Please do not forget to attach any documentation pertaining to the above questions.

APPENDIX B STATE ROAD DESIGN MANUALS AND TECHNICAL SPECIFICATIONS

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