Impacts of Modern Headlights on the Design of Sag Vertical Curves

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ABSTRACT

Headlight sight distance has served for about 65 years as the typical method for calculating the length of sag vertical curves. The headlight sight distance is based on a 1° upward divergence of the headlamp beam. The design criterion for headlamp performance was developed in the 1930s and there is little documentation on the origin of the criterion. There have been significant changes in headlight performance in the intervening years, particularly in the last two decades as automobile manufacturers have shifted away from the use of sealed beam headlamps. Modern headlamps project noticeably less light above the horizontal plane than the older style sealed beam headlamps. This means that modern headlamps project less light (luminance) on the pavement surface at the far end of a sag vertical curve at the 1° upward angle used in design. The objective of the research described in this paper was to compare the performance of modern headlamps with sealed beam headlamps to determine if there is a valid basis for reexamining the criteria for sag curve design. The research method included both a theoretical evaluation using a range of headlamp intensity matrices to calculate the luminance on the pavement in a sag curve and the measurement of luminance for a limited sample of vehicles with modern headlamps and older style sealed beam headlamps. The theoretical analysis utilized procedures developed for the analysis of traffic sign retroreflectivity and modified the application to calculate the amount of luminance on the pavement surface for a sag vertical curve at the stopping sight distance. The analysis utilized a range of headlamp performance matrices including sealed beam headlamps and market-weighted headlamps from several recent model years of vehicles. Based on the theoretical analysis, the upward divergent headlamp angle used in the sag curve design equation should be reduced from 1º to a value between 0.75º and 0.85º. The field analysis indicated a significant difference in illuminance levels from the theoretical analysis, but the results also indicate a need to reduce the headlamp angle used in sag curve design.

INTRODUCTION

Headlamps have been a critical element of the roadway-vehicle-driver system from the earliest days of automobile travel. Vehicle headlamps are the primary means of illuminating the roadway for a driver at night. Despite their importance, they are not incorporated into many aspects of roadway design except for the case of traffic sign and pavement marking retroreflectivity and the design of sag vertical curves.

In 1954, the American Association of State Highway Officials (AASHO) published *A Policy on Geometric Design of Rural Highways*, also known as the Blue Book (*1*). This document was one of the first national geometric design guides and established basic principles for highway geometric design, including the design of sag vertical curves. The Blue Book defined four criteria for sag curve design: headlamp sight distance, passenger comfort, drainage control, and general appearance. Of these, the headlamp sight distance is typically used to design a sag curve. When the headlamp sight distance criterion was originally developed before World War II, sealed beam headlamps were the only type of vehicle headlamp used in the United

States. However, over the last 15-20 years, U.S. vehicle headlamps have changed considerably, as headlamp technology has moved away from sealed beam headlamps. Modern headlamps project significantly less light above the horizontal plane in comparison to the sealed beam headlamps that were used on vehicles into the mid-1980s and earlier. While modern headlamps are considerably different from those of 50 years ago, the sag curve design criteria in the current American Association of State Highway and Transportation Officials (AASHTO) geometric design policy (Green Book) (*2*) are the same as they were in the 1954 edition except for minor changes in some of the input factors.

This paper describes exploratory research conducted to assess the validity of the current sag curve headlamp design criterion. The effort included both a theoretical analysis of headlamp performance using various headlamp profiles and a limited field comparison of a modern headlamp and a sealed beam headlamp.

BACKGROUND

A roadway's vertical grades are typically established by the terrain. Where the grade changes, a vertical curve is used to connect the two grades. Vertical curves are one of the critical elements of geometric design, as they provide the means of connecting vertical tangents in a manner that provides safe and comfortable operation, pleasing appearance, and adequate drainage. The two types of vertical curves are crest curves (where the approach grade is greater than the departure grade) and sag curves (where the approach grade is less than the departure grade). In the United States, vertical curve design is based on a parabolic shape with the curve centered on the vertical point of intersection. A major role for the roadway designer addressing vertical alignment is to select the proper length of a vertical curve that will provide safe and efficient operations, while minimizing the cost of construction.

In a crest curve, sight distance can be blocked if the curve is too short. In a sag curve, the sight distance will not be blocked unless there is an overhead obstruction. Instead, the length is determined by the sight distance provided at night by the vehicle's headlamps as illustrated in Figure 1. In some cases, the other design criteria (passenger comfort, drainage control, and general appearance) may define the appropriate length of sag curve.

The current sag curve headlamp design criteria, shown in Equations 1 and 2 below, are based upon the sight distance provided by headlamps mounted 2.0 ft (0.6 m) above the pavement along a beam that projects light at an angle of 1° above the vehicle's horizontal axis (h and α in Equations 1 and 2). The sight distance used in these equations (S) is assumed to be the same as the stopping sight distance.

For S < L

$$L = \frac{AS^2}{200[h + S \tan\alpha]} \qquad \text{Equation 1}$$

For S > L

$$L = 2S - \frac{200[h + S \tan\alpha]}{A} \qquad \text{Equation 2}$$

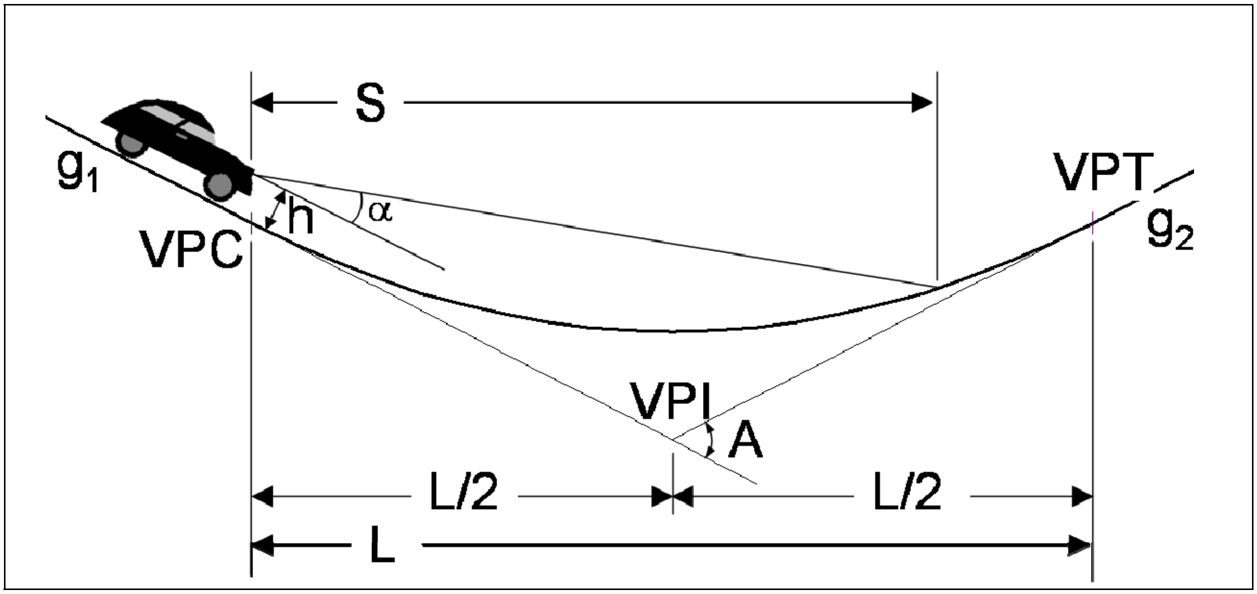

FIGURE 1 Typical Sag Vertical Curve.

where:

L = length of sag vertical curve (measured horizontally), ft (m)
S = light beam distance (equal to the stopping sight distance), ft (m)
A = algebraic difference in grades, percent
α = upward angle of headlamp beam (assumed to be 1°), degrees
h = headlamp height (assumed to be 2.0 ft [0.6 m]), ft (m)

Even though sag curve design is based on headlamp sight distance, previous research indicates that drivers can easily out-drive the visibility provided by headlamps for objects that are not retroreflective (*3*). For a small or low-contrast object, the expected maximum visibility distance is about 425 ft (130 m) (*3*). This corresponds to a speed of about 50 mph (80 km/h). For an object to be detected at night beyond this distance, it must be large, provide high contrast, or be retroreflective. It is the retroreflective elements of the road, such as traffic signs, pavement markings, and delineators, which provide long-distance identification of the roadway alignment for the driver.

The development of design criteria for sag vertical curves appears to have taken place in the late 1930s. In the earliest identified reference to the use of headlamp sight distance relative to sag vertical curves, Noble indicated the upward beam that provided maximum visibility occurred at 0.38º, but he also recognized that the sag curve lengths associated with this angle were excessive (*4*). Noble references a paper by Giessler as the source of the headlamp performance information (*5*). A later paper by Noble describes how headlamp sight distance was used to develop design criteria for the Pennsylvania Turnpike (*6*). This paper indicated the use of the 1º angle and a longer perception and braking reaction time "due to slower human reaction at night" and a chart showing recommended curve lengths as a function of sight distance and algebraic difference in grade. This chart suggested sag curve lengths that are considerably longer than current guidelines for conditions when $S<L$. Thompson later converted the Pennsylvania Turnpike chart to a chart similar to the current AASHTO K value chart, which was supported by

a derivation of the equation for determining sag curve length for both S<L and S>L (*7*). The equations presented in Thompson's paper are the same as Equations 1 and 2. The equations developed by Thompson were incorporated into the 1954 Blue Book design policy as the primary design criteria for the length of sag vertical curves (*1*).

Table 1 provides a comparison if the 1954 and 2004 sag curve design criteria. The changes in the two of the design criteria can be attributed to changes in the input data. In the 1965 policy for rural highway design, AASHO changed the headlamp height from 2.5 ft (0.76 m) to 2.0 ft (0.6 m) (*8*) and the minimum grade for drainage changed from 0.35 percent to 0.30 percent in the 1984 policy (*9*). The comfort and appearance criteria did not change between 1954 and 2004. It is worth noting that the stopping sight distance in 2004 is about 20 percent longer for the higher speeds than it was in 1954. The 1954 Blue Book appears to be the first national guidance to promote design criteria for calculating the length of sag vertical curves, as evidenced by the statement in the book that "*at present, there is not single, widely used, design criterion for establishing lengths of sag vertical curves.*"

TABLE 1 Comparison of 1954 and 2004 AASHTO Sag Curve Design Criteria

Design Policy	**Headlamp Sight Distance** **S < L**	**S > L**	**Comfort**	**Drainage**	**Appearance**
1954 Blue Book	$L = \frac{AS^2}{500+3.5S}$	$L = 2S - \frac{500+3.5S}{A}$	$L = \frac{AS^2}{46.5}$	$L = 143A$	$L = 100A$
2004 Green Book	$L = \frac{AS^2}{400+3.5S}$	$L = 2S - \frac{400+3.5S}{A}$	$L = \frac{AS^2}{46.5}$	$L = 167A$	$L = 100A$

Note: Equations are for customary English units.

To understand why 1° may no longer be the appropriate value to use for the α angle in the sag curve length equations, it is necessary to understand how vehicle headlamps have changed. The sealed beam headlamp, which is the basis for the current sag curve length equations, was in widespread use by 1940. The sealed beam headlamp contains the reflector, filament, and lens as a complete sealed unit. It plugged into the electrical system and could be aimed through the use of adjustable mounting screws. The sealed beam headlamp was the standard light for all U.S. vehicles from the 1940s into the mid-1980s. Replaceable bulb, variable shape headlamps were first permitted in the U.S. in 1984 and from the mid-1980s on, headlamps began to assume a wide range of appearances. Complex-reflector headlamps first began to appear in the late 1980s. Many headlamp systems in the 1990s utilized clear, non-faceted lenses. Headlamps in the U.S. are required to conform to Federal Motor Vehicle Safety Standard 108, which establishes minimum and maximum luminous intensity values at specific measurement points (*10*). This standard establishes the performance characteristics for headlamps and provides a degree of uniformity in headlamp performance.

Not only has there been a change in headlamps, there has also been a change in the beam patterns (pattern of light distribution) produced by vehicle headlamps. During the 1990s, U.S. headlamps began to evolve from headlamps that met only the U.S. standards to "harmonized beam patterns" that would meet headlamp standards in the U.S. and other countries. Because beam patterns in other countries emphasize reduced glare for oncoming drivers, there is less light projected above the horizontal plane. This in turn reduces the amount of light available for sign retroreflectivity and for sight distance on sag vertical curves. This change in headlamp performance has gone largely unnoticed by the transportation engineering community with a few exceptions. One of the most significant of these is research conducted by Carlson and Hawkins and sponsored by the Federal Highway Administration to address minimum retroreflectivity guidelines for traffic signs (*11*). Carlson and Hawkins identified the reduced levels of headlamp lighting above the horizontal plane and the impacts of headlamp design on sign retroreflectivity. Hawkins recognized the potential impacts that headlamp changes could have on sag curve design and conducted exploratory research with a graduate student as part of an unfunded research effort. The goal of that effort was to determine if the reduced amount of light above the horizontal plane associated with modern headlamps supports the need to reassess sag vertical curve design criteria.

ASSESSMENT PROCEDURE

The research effort consisted of two separate assessments that evaluated the impact of headlamp performance on sag curve design. The theoretical assessment calculated illuminance levels of the pavement surface of a sag curve using available headlamp performance matrices. The author compared illuminance levels for several different headlamps, including sealed beam and modern ones. The field assessment measured the illuminance levels on a simulated sag curve for several vehicles that represented both sealed beam and modern headlamps.

Theoretical Analysis of Headlamp Impacts on Sag Curve Design

The first element of the assessment process was to use readily available information and analysis tools to compare pavement surface illuminance levels for sealed beam and modern headlamps. The details of this analysis are described in a separate paper and summarized here (*12*). For the analysis, the research used the Avery-Dennison ERGO program to calculate the illuminance level on the pavement surface for a range of headlamp profiles (*13*). Because the author could find no documentation for the illuminance level upon which the original sealed beam design criteria were based, he took the approach of adjusting the headlamp angle for the modern headlamp to produce the same amount of illuminance on the road surface as the sealed beam headlamp.

To conduct the analysis, the author selected five headlamps to analyze in ERGO. Each headlamp had a headlamp performance profile that specified the luminous intensity, which defines the amount of light produced by the headlamp in a given direction. The directional component of the luminous intensity is measured in angles relative to the horizon (vertical degrees above or below a horizontal line) and the forward projection of the lamp (horizontal degrees left or right of a vertical line). Headlamp profiles are available from measurement laboratories, where the luminous intensity is measured using standard testing procedures. The laboratory tests use new headlamps that are properly aimed and at a specified test voltage. The sealed beam headlamp profile represents an actual sealed beam headlamp. The other four headlamps are composite profiles that were created by averaging headlamp performance values from a range of vehicle headlamps. The five headlamps used in the analysis are listed below:

- Pre-1985: Average of 2 halogen 100×165 mm sealed beam headlamps (2A1). The pre-1985 headlamp is a sealed beam style intended to represent the type of headlamp used when the headlamp sight distance design criterion was developed for the sag vertical curve, and which was the primary type of headlamp until the mid-1980s. This particular headlamp profile represents a rectangular headlamp, which was not introduced until the mid-1970s. Furthermore, it is a halogen lamp, which was not used until the late 1970s (*14*).
- 1985-1990: 50th percentile low-beam headlamp derived from 26 U.S. headlamps from vehicle model years 1985-1990. This profile represents a composite of headlamp styles that were in use in the last half of the 1980s as headlamps transitioned from sealed beam to replaceable bulb headlamps (*15*).
- 1997: 50th percentile market-weighted low-beam headlamps from 35 headlamps from 23 best-selling vehicles for model year 1997. Does not include VOAs or HIDs. There are different profiles for the passenger cars and the light truck/van vehicle types (*16*).
- 2000: 50th percentile market-weighted low-beam headlamps from 20 headlamps from 20 best-selling passenger car vehicles for model year 2000. Does not include HIDs (*17*).
- 2004: 50th percentile market-weighted low-beam headlamps from 20 headlamps from 20 best-selling passenger car vehicles for model year 2004. The vehicles sampled represent 39 percent of all vehicles sold in the U.S. (*18*).

The analysis procedure was based on using the selected headlamp profiles with a passenger car that had a headlamp height of 2.0 ft (0.6 m). The use of this height is conservative in that the sag curve length increases as the height of the headlamp decreases. The author selected speeds of 30, 50, and 70 mph (50, 80, and 110 km/h) and the corresponding stopping sight distance for the analysis. Using ERGO, the author calculated the illuminance falling across the road surface (left side of lane to right side of lane) at a point in space equal to the stopping sight distance from the vehicle and at an upward angle of 1º. Figure 2 illustrates the set up for the analysis and Table 2 presents the results.

The results indicate that the greatest difference in illuminance occurs between the sealed beam and the model year 2000 composite headlamp. To determine the theoretical impact of modern headlamps on sag curve design, the author then used ERGO to calculate the average illuminance for the 2000 year headlamp using an upward angle (α in Equation 1 and Figure 1) ranging from 0.70º to 0.85º at increments of 0.05º as shown in Figure 3. The results indicated that the illuminance difference between the sealed beam and the year 2000 headlamps was smallest at 0.75º. In her thesis, Gogula conducted a similar analysis, but used the 2004 headlamp as the basis of comparison (*19*). She found that for the model year 2004 headlamp, the angle that provided equivalent illuminance was 0.85º (*19*).

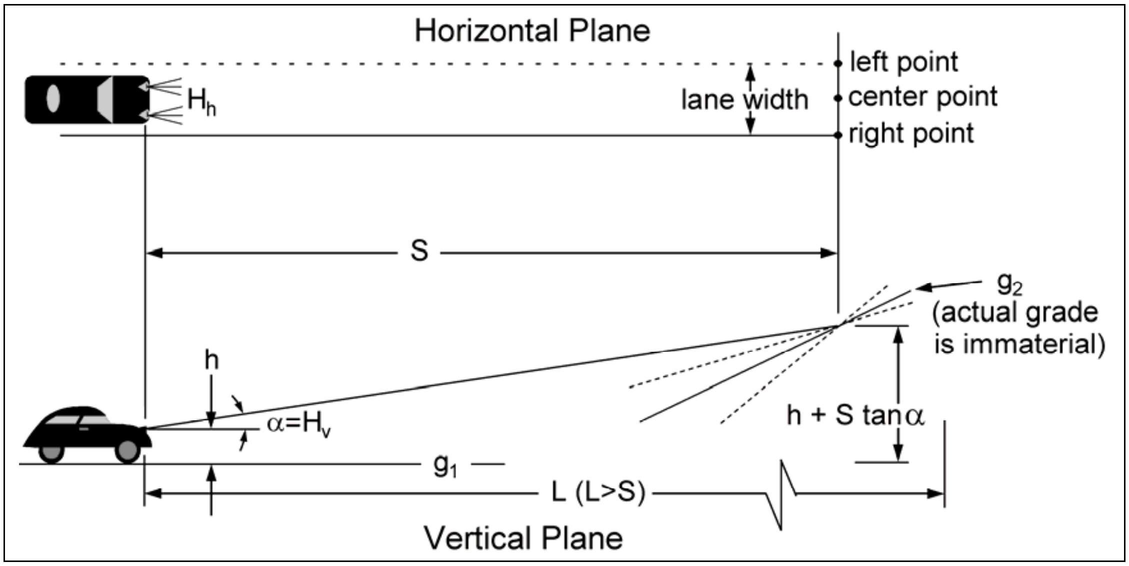

FIGURE 2 Analysis Approach.

TABLE 2 Illuminance Values for 70 mph (110 km/h) Design Speed

Position of Point in Lane	Average Illuminance for the Indicated Headlamp (lux)				
	Pre 1985	**1985-1990**	**1997**	**2000**	**2004**
Left Edge of Lane	0.026447	0.030369	0.020673	0.02032	0.024485
Center of Lane	0.029276	0.033077	0.02387	0.02097	0.024755
Right Edge of Lane	0.031837	0.037036	0.026708	0.02184	0.024307
Average	0.029186	0.033494	0.023751	0.02104	0.024515
Percent Change in the Average from Sealed Beam Headlamp (pre-1985)	0.0%	14.8%	-18.6%	-27.9%	-16.0%

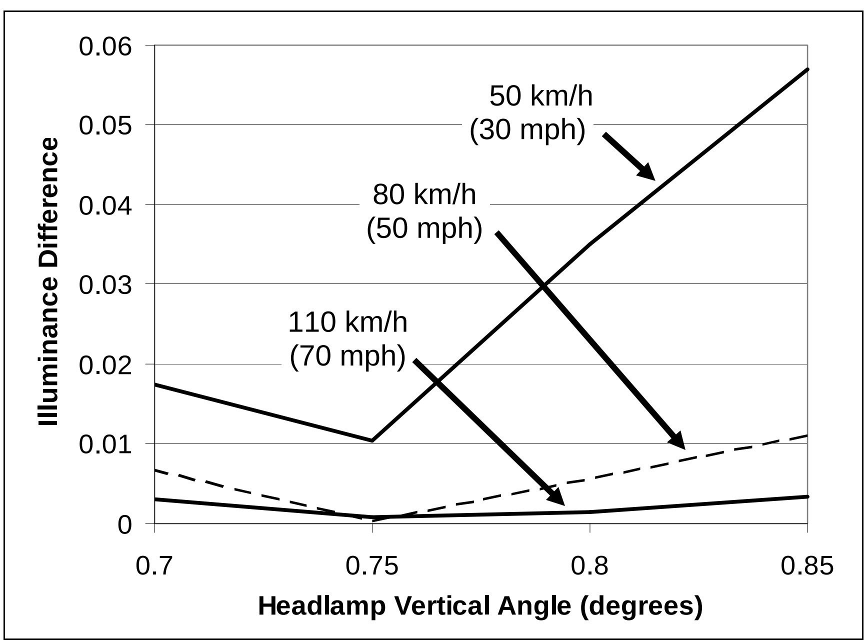

FIGURE 3 Illuminance Difference between Sealed Beam and 2000 Headlamp

The results from the two theoretical efforts, while resulting in a different value for α in Equation 1 or 2, clearly indicate the impact that modern headlamps have on sag curve design and that the upward headlamp beam angle needs to be reduced from 1° to accommodate modern headlamps. Based on the theoretical analysis for the worst case scenario (2000 year headlamps), the K values for sag curves should change from 37, 96, and 181 to 43, 119, and 231 for design speeds of 30, 50, and 70 mph (from 13, 30, and 55 to 15, 37, and 70 for design speeds of 50, 80, and 110 km/h) to equate sag curve design of a modern headlamp (model year 2000) to that of a sealed beam headlamp.

Field Assessment of Headlamp Impacts on Sag Curve Design

In real-world conditions, there may be differences between the actual and theoretical illuminance produced by headlamps. These differences may be due to misaimed headlamps, light scatter or other degradation due to weathering of the headlamp lens, or there can be variations in the supplied voltage that increase or decrease the light output. These real-world conditions can lead to headlamp performance that may be significantly different from the predicted theoretical performance. To assess the difference, researchers measured the actual illuminance produced by a sample of vehicles with sealed beam and modern headlamps for comparison to the illuminance values calculated in the theoretical analysis (*19*).

The field study was conducted on a runway at the Texas A&M University Riverside Campus (an old Air Force Base), where researchers could simulate a sag vertical curve for a 70 mph (110 km/h) roadway and make illuminance measurements without impacting or being exposed to traffic. In the experiment, researchers measured the illuminance produced by four vehicles, two with modern headlamps and two with sealed beam headlamps. Researchers simulated the sag vertical curve by assuming an initial grade (g_1) of 0 percent and measuring the illuminance at a distance and height that could be equated with that of a sag curve. The actual initial grade used is not important as long as the grade is constant. The key was establishing a base condition where the vehicle plane is parallel to the pavement plane. Because the illuminance meter was not sensitive enough to measure the low illuminance levels present at the desired sight distance, the measurements were made at shorter distances and then converted to values that represented a greater distance. The resulting illuminance values were then compared to the theoretical values for 70 mph (110 km/h).

Test Vehicles

Four vehicles were used for the field measurements. Two were Chevrolet three quarter ton light trucks (model years 1995 and 1997) with sealed beam headlamps (130×190, type 2B1). The other two were Ford Taurus cars (both model year 2003) with modern headlamps (VOR headlamps with reflector optics). The researchers measured the headlamp height and headlamp separation dimensions on each vehicle for use in converting measured illuminance to illuminance values at the desired distances. Prior to taking the illuminance measurements, the researchers aimed the headlamps of each vehicle according to the manufacturers' guidelines.

Experimental Procedure

The researchers used a Minolta T12 illuminance meter with remote photometer sensors to make the illuminance measurements. Due to the instrument's lack of ability to measure low illuminance levels, it was not possible to take the illuminance measurements at the 730 ft (220 m) stopping sight distance associated with a 70 mph (110 km/h) speed. Therefore, the measurements were made at distances of 125, 250, and 500 ft (38, 76, and 153 m). The measurement locations were selected to represent vertical angles of 0.5º and 1.0º and horizontal angles that represented 2 ft (0.6 m) intervals across the lane at the stopping sight distance. Basing the measurement locations on horizontal angles provided the researchers with the ability to convert the measurements to luminous intensity at the headlamp and then to calculate illuminance at 730 ft (220 m). The remote sensor probes were mounted on a vertical screen which was marked with the desired measurement locations. The measurement locations varied to correspond to the headlamp height, headlamp separation, and distance for each vehicle. A laser pointer mounted on the vehicle provided appropriate and consistent alignment of the vehicles with the measurement screen.

All field measurements were made at night in a dark environment and the ambient illumination was subtracted from the measurements. The runway where the measurements were made is in a rural area and the ambient illumination levels were measured at 0 ft-c throughout the test procedure. The researchers recorded the illuminance measurements for each headlamp separately by covering one headlamp at a time. The researchers also placed a screen in front of the vehicle (with a height just below that of the headlamp) to reduce the amount of light being reflected from the pavement to the measurement point. Previous research found that when such screens were used, the correlation between the measured direct illuminance and the illuminance estimated by the traditional photometric modeling process is high (99 percent correlation coefficient) (*14*). While the amount of reflected light may contribute to sag curve visibility, Carlson found that the contribution of indirect illuminance was small, particularly at distances that are consistent with stopping sight distances used in sag curve design (*14*). While making the illuminance measurements from the headlamps, the researchers also recorded the voltage at the battery terminals. Voltages ranged from 13.65v to 13.90v for the four vehicles, compared to the 12.8v which is used when measuring headlamp performance for creating the headlamp profiles. The illuminance values were measured at distances of 125, 250, and 500 ft (38, 76, and 153 m).

Data Analysis

Once the data was collected, the researchers used the measured illuminance values to calculate the illuminance at the stopping sight distance for 70 mph (110 km/h). The measured illuminance values at each of the measurement distances were converted to the luminous intensity for a specific horizontal and vertical angle combination using Equation 3. The 10.74 value in the formula is necessary to convert the luminous intensity to SI units. These luminous intensity values were then averaged and used to calculate the illuminance at 730 ft (220 m) across the width of the lane for vertical angles of 0.5º and 1.0º. Illuminance was calculated individually for each headlamp and these were added to get the total illuminance. Table 3 presents the calculated illuminance values on the pavement surface for a 70 mph (110 km/h) sag curve.

$$I = \frac{E}{10.74} \times \frac{S}{\cos\alpha}^{2}$$ Equation 3

where:

I = luminous intensity (candela)
E = illuminance (lux)
S = distance (ft)

TABLE 3 Results of Field Measurements

Distance to the left of the right edge line	Illuminance (lux) for Headlamp and Vertical Angle*			
	Sealed Beam at 1.0º	Sealed Beam at 0.5º	Modern at 1.0º	Modern at 0.5º
12 ft (3.6 m)	0.090	0.171	0.050	0.122
10 ft (3.0 m)	0.093	0.178	0.052	0.132
8 ft (2.4 m)	0.097	0.184	0.052	0.131
6 ft (1.8 m)	0.101	0.196	0.053	0.136
4 ft (1.2 m)	0.103	0.203	0.056	0.137
2 ft (0.6 m)	0.105	0.213	0.058	0.148
0	0.104	0.219	0.056	0.145
Average	0.099	0.195	0.054	0.136
Percent Change in the Average from Sealed Beam at 1.0º	0.0%	+97.0%	-45.5%	+37.4%

Note: *Illuminance values are calculated for a distance of 730 ft (220 m) based on the average measured luminance at 125, 250, and 500 ft (38, 76, and 153 m). Illuminance values for each type of headlamp are an average of two vehicles.

COMPARISON OF THEORETICAL AND FIELD MEASUREMENTS

The next step in the assessment process was to compare the results of the theoretical and field measurements. Such a comparison is not as simple as a direct comparison of the illuminance values. The amount of light produced by a vehicle's headlamps (luminous intensity) is directly related to the amount of voltage supplied to the headlamps. In laboratory tests from which headlamp profiles are developed, a constant voltage of 12.8v is applied to the headlamps. As indicated previously, the voltages ranged from 13.65v to 13.90v for the test vehicles used in the field measurements. Therefore, the luminous intensity (and by definition the illuminance) was adjusted using Equation 4. Based on the average of the voltages measured in the test vehicles, the theoretical illuminance values should be increased by 1.29 to provide values that are comparable to those measured in the field. The comparison of the theoretical and field values was further complicated by the fact that the headlamps profiles used in the theoretical analysis were not the same as the headlamps used in the field analysis. This inconsistency was due to the fact that this research effort was unfunded and the researchers were limited to available headlamp profiles and vehicles in the theoretical and field analysis. Given this limitation, the researchers elected to compare the modern headlamp in the field analysis (2003 Taurus) to the 2004 headlamp profile in the theoretical analysis and the sealed beam headlamp in the field analysis (1995 and 1997 trucks) to the pre-1985 sealed beam headlamp. Table 4 presents the results of the comparison.

$$LI_{vc} = LI_{tv} * (\frac{V_2}{V_1})^{3.4}$$ Equation 4

where:

LI_{vc} = Voltage-corrected luminous intensity
LI_{tv}= Luminous intensity at test voltage
V_1= Test voltage
V_2= Operating voltage

TABLE 4 Comparison of Theoretical and Field Illuminance Measurements

Position of Point in Lane	**Illuminance Across the Lane for the Indicated Headlamp (lux)**					
	Theoretical Measurement				**Field Measurement at 1.0°**	
	Theoretical Pre 1985	**Adjusted Pre-1985[a]**	**Theoretical 2004**	**Adjusted 2004[b]**	**Late 1990s Sealed Beam**	**2003 Taurus**
Left Edge	0.026447	0.034961	0.024485	0.030774	0.090	0.050
Center	0.029276	0.038701	0.024755	0.031113	0.101	0.053
Right Edge	0.031837	0.042086	0.024307	0.030550	0.104	0.056
Average	0.029186	0.038582	0.024515	0.030811	0.098	0.053

Notes: [a]Theoretical sealed beam headlamp adjustment factor = 1.321
[b]Theoretical 2004 headlamp adjustment factor = 1.257

Table 4 indicates that there are significant differences between the theoretical and field measurements, with the field measurements being significantly greater than the theoretical measurements. These differences can be attributed to several different factors. Among those previously mentioned are differences in voltage and differences between the headlamp profiles and the headlamps used in the field study. Other potential factors that could account for the differences include the following:

- Headlamp aim – although the researchers aimed the headlamp on the test vehicles prior to conducting the field tests, the aiming process is not as precise as the laboratory setup and could account for differences in performance.
- Degradation of the headlamps – the headlamps of the test vehicles had been in regular use for periods between 2 and 10 years. Some of the headlamps lens exhibited glazing, hairline cracking, or other types of degradation that could cause light scatter.

CONCLUSIONS AND RECOMMENDATIONS

Vehicle headlamps help in improving the visibility of the roadway at night. Typically, sag curve design is based on the available headlight sight distance. The research shows that changes in headlamps over the past 20 years have resulted in reduction of light reaching road signs. This indicates a reduction in the light produced above the horizontal axis of modern headlamps. There is a need to understand the impact this change in headlamps might have on the design of sag curves. This research presented a limited evaluation of the impact of headlamp performance on the illuminance provided on sag curves; and the findings clearly indicate that the illumination provided at 1º by modern headlamps is less than that provided by sealed beam headlamps. This indicates a need to reevaluate the headlamp sight distance design criterion for sag vertical curve length. There are many significant issues to be addressed in a more detailed analysis of sag curve design criteria, several of which are listed below. The author did not address any of these in the exploratory research.

- How are modern headlamps different from those used to develop the sag curve design criteria?
- How will headlamp performance change in the future?
- What are the sag curve illuminance needs for the driving population?
- Should the headlamp sight distance sag curve design criteria be based on the performance of new and properly aimed headlamps or performance that better represents degraded and misaligned headlamps?
- Should low-beam or high-beam headlamps be the basis of sag curve design?
- What headlamp should serve as the basis for sag curve design?
- Headlamps do not provide sufficient sight distance for high-speed nighttime driving on flat and straight alignment. If this is the case, how can they be used as the basis for high-speed design on sag curves?
- Is there a relationship between sag curve design, modern headlamp performance, and safety?

Headlamp Divergence Angle

The equations for calculating the length of a sag vertical curve (see Equations 1 and 2) have used a 1º upward divergence angle for the headlamp beam since the equations were first presented to the AASHTO design policy in 1954. At that time, all vehicles were equipped with sealed beam headlamps, which project a fair amount of light above the horizontal. Many, if not most, of the modern headlamps have a strong cut-off pattern, and project significantly less light above the horizontal plane than sealed beam headlamps. The headlamp analysis described in this paper found that, for the headlamp profile that represents the top selling 2000 model year passenger vehicles, using an angle of 0.75º in the sag vertical curve length equation provides the illumination level that is closest to a sealed beam headlamp. For the 2004 model year passenger vehicles, a divergent angle of 0.85º provides the illumination level that is closest to a sealed beam headlamp.

Headlamp Performance

The analysis described in this paper is based on a limited number of headlamp profiles and may not adequately represent actual trends in headlamp performance. Future analysis should include better sampling of modern headlamps and their associated performance. In addition to the sampling issues, there are many other factors that can impact headlamp performance, including voltage, aim, bulb output, and lens degradation. The headlamp profiles used in this analysis represent the performance of new headlamps that are properly aimed and measured in laboratory conditions. These ideal conditions are not typical of those experienced in real-world conditions. Therefore, future analysis should also evaluate the performance of real-world headlamps and quantify real-world factors that impact performance. Because headlamp performance has a significant impact on nighttime driving, particularly from a safety perspective, the transportation engineering profession should focus greater resources on assessing the impact of headlamp performance on the roadway infrastructure and take a more active role in working with other professions that are responsible for maintaining headlamp standards.

SUMMARY

This paper describes the impact of headlamp performance on sag vertical curve design and clearly indicates that modern headlamps produce lower illumination levels above the horizontal plane than the headlamps that were used to develop the sag curve design criteria. Based on the analysis described in this paper, it appears appropriate to reduce the size of the upward divergence of the headlamp beam from the 1º used for 50 years to a value between 0.75º and 0.85º.

This analysis clearly indicates a technically-based need for a reduction of the headlamp beam angle. However, establishing a practical need for such a change was beyond the scope of this effort. There is no known evidence suggesting a nighttime safety concern related to the length of sag vertical curves. This issue should be considered in future efforts.

Many different aspects of geometric design criteria have been reassessed and modified in recent years as research has identified changes in vehicle technologies, driver limitations, and other factors that impact geometric design. However, there have been no changes in sag vertical curve design criteria for over 50 years, despite the fact that there have been significant changes in headlamps and driver needs during the same period. It appears appropriate to focus attention on this issue to establish a more solid foundation for the headlamp design criteria used for sag vertical curves. Vehicle headlamps have changed significantly in the last 15 years and will continue to change in the near future. The transportation engineering profession should take note of these changes and better incorporate this knowledge into design and operational decisions.

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