THE IMPACT OF MODERN HEADLAMPS ON THE DESIGN OF SAG VERTICAL CURVES

A Thesis

by

MADHURI GOGULA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2006

Major Subject: Civil Engineering

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Approved by:

Chair of Committee,	H. Gene Hawkins
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ABSTRACT

The Impact of Modern Headlamps on the Design of

Sag Vertical Curves. (May 2006)

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Incorporating safety in the design of a highway is one of the foremost duties of a design engineer. Design guidelines provide standards that help engineers include safety in the design of various geometric features. However, design guidelines are not frequently revised and do not accommodate for the frequent changes in vehicle design. One such example is the change in vehicle headlamps. These changes significantly impact the illuminance provided on the road and in turn the design formula.

Roadway visibility is critical for nighttime driving. In the absence of roadway lighting, vehicle headlamps illuminate the road ahead of a vehicle. Sag vertical curve design depends on the available headlight sight distance provided by the 1 degree upward diverging headlamp beam. The sag curve design formulas were developed in the early 1940s when sealed beam headlamps were predominant. However, headlamps have changed significantly and modern headlamps project less light above the horizontal axis. In this research, the difference in illuminance provided by sealed beam headlamps and modern headlamps was examined. For the theoretical analysis, three different sag curves were analyzed. On these curves, about 26 percent reduction in illuminance was observed at a distance equal to the stopping sight distance when comparing sealed beam to modern headlamps. A change in the headlamp divergence angle from 1.0 degree to 0.85 degree will provide the required illuminance on the road when using modern headlamps. A field study was performed to validate the theoretical calculations. It was observed that for modern headlamps, a divergence angle less than 1 degree and greater than 0.5 degrees will provide illuminance values comparable to sealed beam headlamps. As a part of this research, a preliminary study, examining the impact of degraded headlamp lenses on the illuminance provided on sag vertical curves was conducted. A significant reduction in illuminance reaching the roadway on sag curves was observed, due to headlamp lens degradation.

ACKNOWLEDGMENTS

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I also appreciate all the staff at the Riverside Campus that helped conduct the field study. I also appreciate the help extended by other graduate students and friends during the course of my research.

I am also thankful to my parents and brother who were with me whenever I needed their support.

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CHAPTER I

INTRODUCTION

When designing a road for night driving, it is important to consider the visibility of the road and other objects on it. A driver must be able to see the path he/she is traveling on to maintain control over the vehicle and stop in time to avoid any object or hazardous condition on the road. Inadequate sight distance results in increased workload on the driver. This makes the task of driving more complex, potentially reducing safety. Crash statistics show that 42 percent of all crashes and 52 percent of fatal crashes occur at night and during other degraded visibility conditions (*1*). Studies have also shown that the nighttime crash rate is about three to four times the crash rate during the day (*2*). This is relatively high considering that the number of vehicle miles traveled is less during the night. Intoxication and fatigue are two factors that account for this high nighttime crash rate (*3*). Even when considering only non-alcohol-related crashes, the nighttime fatal crash rate is twice the daytime crash rate (*2*). Some studies have also identified that crashes during night are higher on unlit roads compared to roads provided with street lighting (*3*). Therefore, it is reasonable to assume that poor visibility contributes to nighttime crashes (*2*).

This thesis follows the style of *Transportation Research Record.*

Automobile headlamps have changed significantly over the last 20 years when observed from the design point. Modern headlamps have different performance characteristics than sealed beam headlamps, as evidenced by recent research on sign retroreflectivity. This research shows that there has been considerable reduction in the amount of light reaching roadway signs. Researchers attributed this to the change in the amount of light produced above the horizontal axis of headlamps (*4, 5*). This change in headlamps could potentially impact the amount of light reaching the roadway on a sag curve. Degraded headlamp lenses might also have an adverse effect on the amount of light emitted from headlamps above the horizontal axis. Modern headlamp lenses are made of polycarbonate or acrylic plastic and are more susceptible to degradation compared to sealed beam headlamps that have lenses made of glass. This degradation is because hard plastic is prone to yellowing, fogging, cracking, pitting, etc. caused by different factors like acid rain, condensation, and high heat. Degraded headlamp lenses might have a significant impact on the amount of light emitted from headlamps.

Design guidelines recommend that a driver should have sufficient visible length of roadway, at least equal to the safe stopping distance, to allow him to stop safely and avoid collisions with other vehicles or obstructions. One of the design criteria for sag vertical curves depends on the sight distance provided by vehicle headlamps. This design criterion for sag curves reflects the requirements and standards of sealed beam headlamps, which are rare in modern vehicles. Therefore it is appropriate to examine the design criteria and identify if they still hold good when using modern headlamps on vehicles.

PROBLEM STATEMENT

Reduced roadway visibility is a key factor contributing to an increased number of crashes occurring at night. The formula used to determine the length of a sag vertical curve depends on the length of roadway that is visible due to the light from the upward divergence of the headlight beam. However, considering the changes occurring in the headlamp beam pattern, modern headlamps have less light directed upward, reducing roadway visibility on sag curves. A study examining the change in the amount of light reaching the road due to changed headlamp design would make it possible to determine the adequacy of the design formula currently in use. A study examining how degraded headlamp lenses scatter light and the resulting impact on the light emitted above the horizontal axis would aid the study in determining the adequacy of the design formula of sag curves.

RESEARCH OBJECTIVES

The objectives of this research are:

- Compare the amount of illuminance produced by sealed beam headlamps on sag curves to the illuminance produced by modern headlamps,
    - for theoretically calculated values.
    - by developing a field procedure to determine the illuminance values in the field.
- Based on the results of the comparison study, recommend changes to the design criteria to accommodate modern headlamps if necessary.

- Evaluate the impact of headlamp lens degradation on the illuminance produced by a headlamp. Determine whether this change is significant to conduct a more detailed study.

THESIS ORGANIZATION

This thesis consists of six chapters. Chapter I presents background information on the nighttime crash rate and sight distance along with a description of the problem statement and research objectives. Chapter II reviews available literature on the design criteria of sag vertical curves, lighting terminology, and different types of headlamps. Chapter III shows the theoretical calculations for illuminance from different headlamps and the comparison of illuminance values between the sealed beam and modern headlamps. Chapter IV describes the field study and the comparison of the illuminance values obtained in the field. Chapter V details the degradation of headlamp lenses study. Chapter VI summarizes the findings of this research and presents the proposed recommendations based on the research results.

CHAPTER II

LITERATURE REVIEW

This chapter contains a review of literature pertaining to existing studies on roadway visibility, headlamps, and the design criteria of sag vertical curves. The lighting criteria section describes the lighting terminology, illuminance criteria, and standards required for nighttime visibility. The section on headlamp trends discusses the different headlamps and how the changes in the beam pattern might affect the visibility of the road. The geometric design section reviews the literature on the design criteria of sag vertical curves.

LIGHTING CRITERIA

Many factors like traffic volume, time of day, speed, weather, and alertness of the driver contribute to roadway safety. The information a driver receives visually contributes to about 80 percent of all the information he needs (*1*). This signifies the importance of roadway visibility for safe driving conditions.

Terminology and Standards

The following lighting terminology is used commonly when designing highways for nighttime driving:

- Luminous intensity (I): The amount of light produced by headlamps in a particular direction. S.I. unit: candelas, (cd). U.S. Customary unit: lumens, (lm).

- Illuminance (E): The amount of light falling on a unit area of the roadway. S.I. unit: lux, (lx). U.S. Customary unit: foot-candles, (ft-c).
- Luminance (L): The amount of light reflected from the roadway. S.I. unit: candelas/m^2, (cd/m^2). U.S. Customary unit: foot-lamberts, (ft-L).

It is difficult to set specific standards dictating the threshold illuminance required on the road as the needs of nighttime drivers are varying. The Illuminating Engineering Society of North America (IESNA) has recommended average illuminance values for road lighting to meet the needs of night traffic. In addition to the headlight illumination from vehicles, they recommend fixed lighting be provided for more distinct visibility of the roadway and traffic (*6*). Table II.1 shows the recommended average illuminance values for fixed lighting on different types of roadways.

TABLE II.1 Recommended Average Illuminance Values for Fixed Roadway Lighting (lx) (*6*)

Road and Area Classification		Pavement Classification			Illuminance Uniformity Ratio E_{avg} to E_{min}
		R1	R2 and R3	R4	
Freeway Class A		6	9	8	3 to 1
Freeway Class B		4	6	5	
Expressway	Commercial	10	14	13	3 to 1
	Intermediate	8	12	10	
	Residential	6	9	8	
Major	Commercial	12	17	15	3 to 1
	Intermediate	9	13	11	
	Residential	6	9	8	
Collector	Commercial	8	12	10	4 to 1
	Intermediate	6	9	8	
	Residential	4	6	5	
Local	Commercial	6	9	8	6 to 1
	Intermediate	5	7	6	
	Residential	3	4	4	

where:

R1: Portland cement, concrete road surface

R2: Asphalt road surface (60 percent gravel)

R3: Regular asphalt road surface

R4: Asphalt road surface with smooth texture.

The illuminance diminishes with distance. The relation between luminous intensity and illuminance is shown by Equation II.1.

$$E = \frac{I * 10.764}{\left(\frac{S}{\cos(\alpha)}\right)^2} \quad \text{(II.1)}$$

where:

E: Illuminance (lx)

I: Luminous intensity (cd)

S: Horizontal distance (ft)

α: Headlight upward divergence angle (degree)

Some of the parameters used in Equation II.1 are shown in Figure II.1.

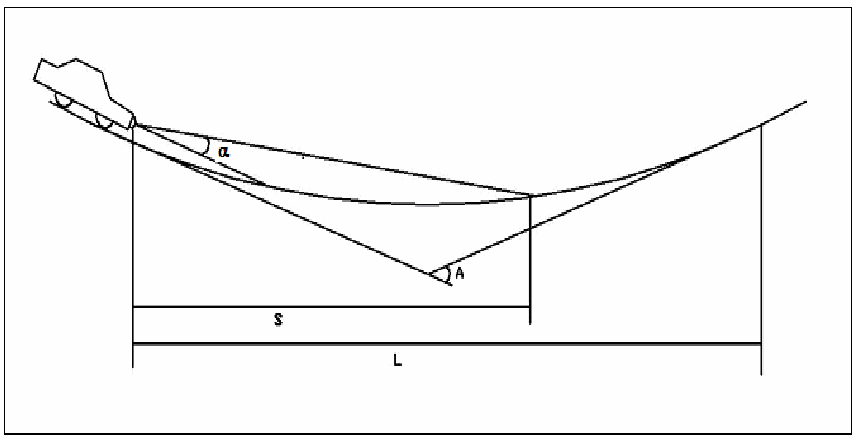


FIGURE II.1 Sag Vertical Curve (*7*)

Roadway Visibility at Night

The amount of light required on the road is a function of different human characteristics like age, alertness, etc. Many researchers (*8, 9, 10, 11, 12*) attempted to quantify visibility requirements, but the human factor component involving perception, recognition, and reaction to an event makes the task of setting a standard difficult (*13*).

Nighttime drivers depend on lane markings to maintain uniform speed and positioning of the vehicle in the lane. To maintain this longitudinal and lateral control, they require proper visibility of the road and the oncoming vehicles (*14*). The amount of light required on the road for the safe operation of a vehicle depends on a number of factors like target reflectivity, contrast, etc. (*15*). Vehicle headlamps provide the source of lighting on unlit highways. The illuminance at a point on an unlit road depends on the geometry of the road, luminous intensity, and position of the headlamps. The use of low beam is common for nighttime driving because the continuous use of high beam causes an uncomfortable glare for the opposing traffic. This factor indicates that improvements to the low beam will enhance roadway visibility at night (*16*).

Research shows that small objects with little contrast when illuminated by low beam headlamps are visible up to a distance of 425 ft on dark highways. This distance of 425 ft corresponds to a safe stopping distance for a speed of 55 mph. Further, it has been determined that a 5-fold increase in light is necessary for 9 mph increase in speed and a 10-fold increase in light is necessary for a decrease in the object size by 50 percent (*17*). This research indicates that a vehicle headlight restricts the sight distance to 425 ft on a dark roadway. The research also showed that a luminance level of 1 cd/m^2 is required to see a high-contrast object at about 525 ft and a speed of 60 mph. Luminance values greater than 1.2 cd/m^2 marginally increase visibility. It was also observed that drivers could detect and react to objects with a luminance value of 0.8 cd/m^2 at a distance of 425 ft. Further it was found that a large proportion of drivers could not detect objects on the roadway at the AASHTO-proposed stopping sight distance of 425 ft corresponding to a speed of 50 mph. However, detection was not a problem when the object was externally illuminated or retroreflective (taillights or side reflectors of vehicles) (*17*).

On sag vertical curves, there is no restriction to the sight distance during daytime or when continuous roadway lighting exists (*14)*. However, the farthest point visible with the aid of headlamps at night is limited due to the geometry. For this reason, design guidelines recommend that sag vertical curves should provide a minimum headlight sight distance equal to the stopping sight distance. The headlight sight distance provided depends on the type of headlights used.

Researchers examined the impact of fixed lighting systems on the accident rate and obtained useful results. However, the same was not possible with headlights because it is difficult to perform controlled studies when using a moving light source for the study (*16*). A recent study conducted by Scott examining the impact of eight different variables on the accident rate at 41 sites showed that as the illuminance at a site increased, the accident rate dropped in an almost linear fashion (*18*). Table II.2 shows the results of another study done 20 years ago. The study analyzed the impact of illuminance on the crash rate by using data from the Fatal Accident Reporting System (FARS). From the table it can be seen that when compared to straight roads, the percentage of accidents occurring on curves is higher during the night under unlit conditions. These data show that improved lighting on curves might reduce the number of accidents on them (*16*).

TABLE II.2 Summary of 1980 Accident Statistics Relating to Lighting Conditions, Road Geometry, and Run-Off Road Accidents (*16*)

Single Vehicle Fatal Accidents as a Function of Lighting and Road Geometry (%)			
	Daylight	Night (but Lighted)	Night (Dark)
Straight and Level	67	64	58
Curved and Level	33	36	42
Straight and Grade	46	45	39
Curved and Grade	55	55	61
All Straight (Level + Grade)	59	59	52
All Curved (Level + Grade)	41	41	48

Detailed studies examining the relationship between the light provided on the road and the corresponding crash statistics help researchers understand the importance of headlamp lighting. Studies performed by Indiana University (*19*) reported that in about 3 percent of the accidents analyzed, better forward lighting would have contributed to preventing accidents. A report by Bhise et al., discussing the distribution of street lighting, showed that street lighting is not common on rural roads. This report suggests that the majority of the high-speed driving is done with the aid of light from headlamps (*20*).

From how far away should an object/person be visible to a driver? Though there is no single answer to this question, several studies attempted to find an answer. A particular value has not been set for the safe visibility distance, but studies show that it depends on a number of criteria, like target reflectivity and contrast. Detection of an obstacle at night requires it to be of sufficient luminance and contrast when compared to its background.

- Target Reflectivity: Reflectivity is the amount of light reflected from the surface of the target. Researchers have also observed that as target reflectivity increases by a factor of 9, the visibility distance increases by about 100 percent (*15*).
- Target Contrast: Contrast is a characteristic of the target which allows to be identified separately from its background. Contrast is necessary for visibility because humans use brightness contrast to detect and identify objects. Thus, contrast is one of the key factors that contributes to visibility at nighttime.
  A change in reflectivity of the target results in a change in contrast. As target reflectivity increases, the average response distance increases considerably because target contrast increases and enhances target detection (*15*).
  Figure II.2 shows how a pedestrian is revealed with the variation in vertical illumination.

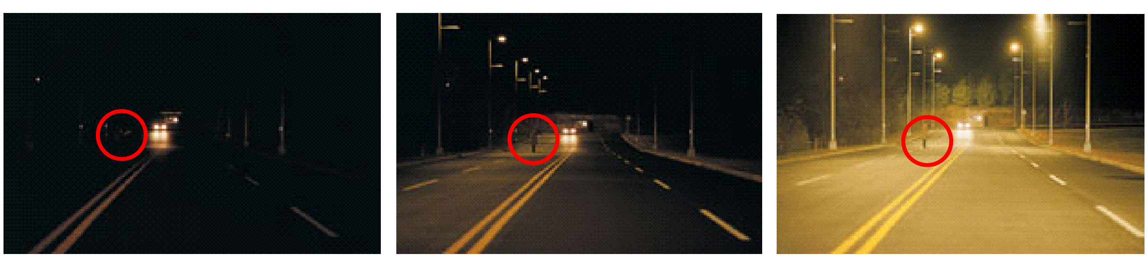


FIGURE II.2 Stages of Varying Vertical Illumination (*2*)

The illuminance required on the road is a function of driver expectance, object reflectance, and the subtended angular area (this depends on the angle subtended by the object on the retinal plane). The illuminance provided depends on the location of the object within the beam pattern and its distance from the headlights (*21*). It is difficult to provide a single illuminance value that would be effective to detect different objects at different positions on the road. Also, human characteristics are variable and depend on many factors like age, vision, time of day, etc. Light from a headlamp illuminates both the target and its background. So, as the headlamp is moved away and its output is increased to provide the same target luminance, the contrast decreases because the background is now relatively closer to the target. Thus, solely increasing the target luminance will not improve the visibility conditions (*16*).

HEADLAMP TRENDS

Headlights are mounted on the front of a car and light the road ahead. They help in proper navigation at night and during reduced visibility conditions. Headlamps have come a long way since the first headlamps which used acetylene or oil in the 1880s (*22*). Figure II.3 shows an acetylene gas headlamp from 1896. The following sections give a brief description of various headlamps and their beam patterns.

FIGURE II.3 Acetylene Gas Headlamps - 1896 (*23*)

Sealed Beam Headlamps

Sealed beam headlamps consist of a single unit assembly comprised of the reflector and filament, in front of which a fused glass lens is fixed (*22*). The unit is filled with gas like any light bulb. Figure II.4 shows a sealed beam headlamp and Figure II.5 shows the filament attached to the lens in a sealed beam headlamp. The beam patterns of the different sealed beam lamps are similar.

Figure II.6 shows the beam pattern of a low beam Computer Analysis of Retroreflectance of Traffic Signs (CARTS) model headlamp. CARTS represents 50^{th} percentile low beam headlamp data obtained from 26 U.S. headlamps consisting of 1985-1990 vehicles (*4*)

FIGURE II.4 Sealed Beam Headlamp

FIGURE II.5 Filament in a Sealed Beam Headlamp (*22*)

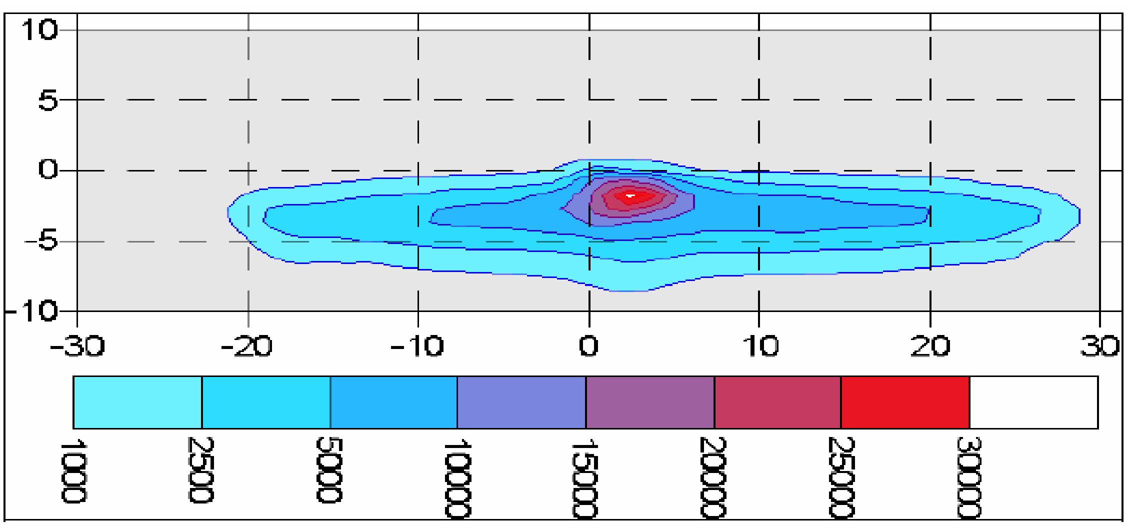


FIGURE II.6 Isocandela Plot of a Low Beam CARTS Median Headlamp (*4*)

Modern Headlamps

Modern headlamps have removable lamps and are no longer sealed to the lens. The housing serves as a reflector and lens, and is made of plastic. These lamps may be comprised of different light emitting diode's (LEDs), high intensity discharge (HID) lamps, and halogen lamps. Halogen headlamps are further comprised of visually optically left (VOL), visually optically right (VOR) lamps, which again use different techniques like projector optics and reflector optics. Figure II.7 shows a projector headlamp.

FIGURE II.7 Projector Headlamp (*24*)

The University of Michigan Transportation Research Institute (UMTRI) created composite median lamp files from headlamp output files of the 10-best selling passenger cars for different years. Based on the sales volume of each vehicle, data in the composite file are weighted. The median lamp represents the median illumination value at each of the measured points. Figure II.8 shows the beam pattern of the 2000 UMTRI median headlamp data. This beam pattern does not represent any particular vehicle on the road (*4*).

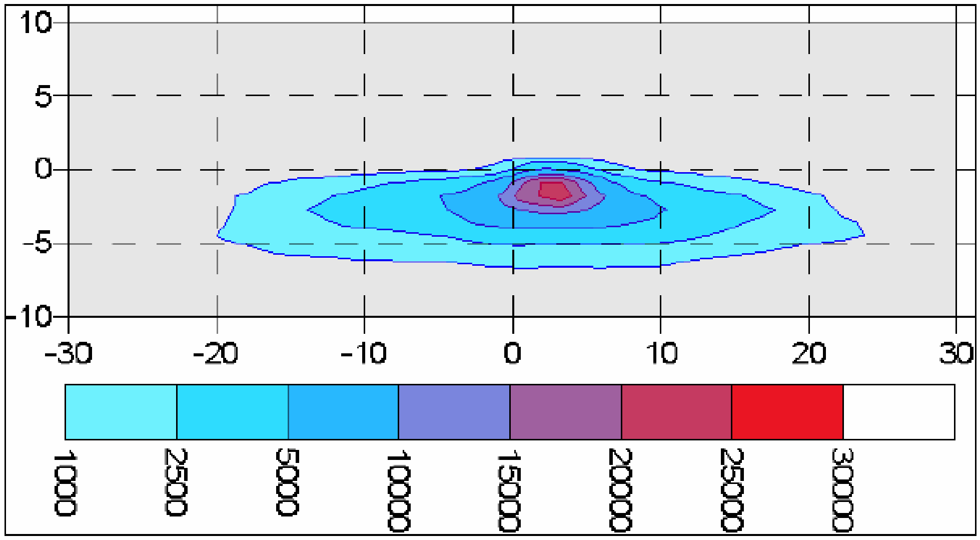


FIGURE II.8 Isocandela Plot of a Low Beam UMTRI 2000 Median Headlamp (*4*)

HID headlamps which are of relatively recent origin are bright headlamps with a blue tinge to them. Metallic salts vaporized within a chamber produce a high-intensity arc. Hard ultraviolet (UV)-absorbing lens shield the ultraviolet light produced by the arc within a HID lamp from escaping. These headlamps require a long warm-up time, so Xenon gas is used to provide minimum light when the headlamp is first turned on. HID lamps produce more light compared to halogen lamps (*22*). Also, HID lamps have a sharper horizontal cut-off beam pattern further reducing the portion of lighted highway on sag curves (*25*).

Light emitting diode is another headlamp that gives out electroluminescence when an electric current is passed through a semiconductor. The color of the light emitted depends on the material of the semiconductor. LEDs are relatively expensive and have some problems with heat-removal techniques. This is a reason they have yet to enter the market (*22*).

The placement, luminous intensity produced, and illuminance from a headlamp are all very important factors contributing to nighttime visibility on sag curves. Automobiles in the U.S. have to follow the standards and specifications set by the Society of Automotive Engineers (SAE) J579 (*26*) and the Federal Motor Vehicle Safety Standards (FMVSS 108) of the National Highway Transportation Safety Administration (NHTSA) (*27*) for headlamps. The light produced above the horizontal axis determines the distance illuminated ahead of a vehicle on a sag curve. However, this light above the horizontal plane of the headlamp (H-H plane) also causes glare to the drivers of vehicles on the opposing lane (i.e., on a two-lane highway without an opaque median separator). U.S. headlamps had a beam pattern that provided more light above the H-H plane when compared to the European and Japanese beam patterns. However, to promote universal headlamp standards, the FMVSS 108 was revised in 1997. The most significant change was the reduction in the amount of light above the H-H plane in U.S headlamps (*28*). A study comparing conventional U.S headlamps, VOL, VOR, and harmonized headlamps showed that there is a considerable decrease in the amount of illumination above the horizontal when observing overhead signs at about 500 ft away (*29*). There is a reduction in overhead illumination by 18 percent when comparing VOR headlamps to conventional U.S. headlamps (of model year 1997), by 28 percent when comparing VOL headlamps and by 33 percent when comparing harmonized headlamps (*28*). A recent Federal Highway Administration (FHWA) sponsored project looked into the illumination provided to traffic signs by the present vehicles. The research showed that unless Type III or brighter sheeting is used, most vehicles will not provide the required illumination to overhead signs. Illumination data from over 1500 headlamp distributions showed that about 50 percent of the vehicles provide the required illumination to overhead signs to meet the legibility criteria (*28*).

Difference in Beam Pattern

Modern headlamps direct comparatively less illuminance above the horizontal axis, which affects the visibility distance on sag vertical curves. The beam pattern above the horizontal cutoff varies significantly and the amount of light above the horizontal appears reduced (*30*). Thus, it might be necessary to review the criteria followed in the design of sag curves and examine their adequacy in meeting the driver's requirements.

OTHER FACTORS AFFECTING THE LIGHT EMITTED FROM HEADLAMPS

The design characteristics of a vehicle, like headlamp height, headlamp aim, voltage at which headlamps operate, and dirt or degradation of the headlamp lenses, have implications on the lighting from a vehicle.

Headlamp Height

FMVSS 108 sets standards for the minimum and maximum headlamp placement heights on a vehicle. Headlamps should be mounted at a minimum height of 1.8 ft and not higher than a height of 4.5 ft from the surface of the ground (*27*). Prior to the 1980s headlamps were mounted 2.0 ft or more above the ground. The mounting height was later reduced to 1.8 ft in the 1980s (*31*). A study performed by Roper and Messe showed that for every inch decrease in the mounting height of the lamp, there is a loss of 10 ft of sight distance (*32*). The formulas in "A Policy on Geometric Design of Rural Highways", also known as the "Blue Book", published by the American Association of State Highway Officials (AASHO) in 1954 used a headlamp mounting height of 2.5 ft for the design of sag vertical curves (*33*). The mounting height was changed to 2.0 ft in the 1965 AASHO Blue Book (*34*).

Headlamp Aim

It is not mandatory in many states across the U.S. to get a vehicle inspected for its headlamp aim as a part of the annual inspection. This lack of inspection has resulted in headlamp misaims far beyond the acceptable range (*35*). Consequently there is a lot of variability in the illumination produced by headlamps. In the 1970s, when Texas had mandatory headlamp aim inspection, a study showed that 68 percent of the headlamps were within the specified SAE limits (*36*). Improper setting of the headlamps, changes in the adjusting mechanism, and the changes due to load on the vehicle are the major causes of headlamp misaim. Even a minor change in the headlamp aim, by about 1 degree, can result in large changes in illumination or glare. Figure II.9 shows a mechanical headlamp aiming device, which is used to adjust the aim of headlamps.

FIGURE II.9 Mechanical Headlamp Aiming Device (*37*)

Voltage

The field operating voltages (when the vehicle is running) for vehicle batteries range between 13.2 to 14.2 volts, with an average voltage around 13.7. This is higher than the test voltage of 12.8. Higher voltage results in higher luminous intensity however, this relationship is not linear. An increase by 7 percent in voltage, from 12.8 to 13.7, would result in a 26 percent increase in luminous intensity (*38*).

Dirt

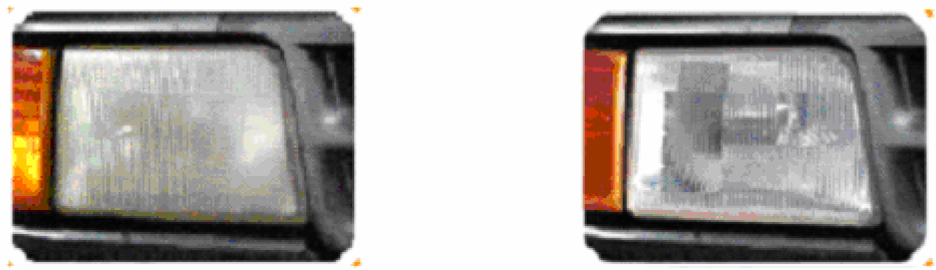
Headlamp intensity decreases as dirt accumulates on the inside or outside the headlamp lens. This decrease in intensity results in a reduction of the visibility distance. A study performed by Cox showed that a moderately dirty headlamp lens could reduce the output of light by 50 percent (*39*).

Scattering of light due to layers of dirt could moderately increase the amount of light directed upwards and also increase the visibility distance. However, research also shows that 50 percent reduction in the amount of light produced could result in 10–15 percent reduction in visible distance (*40*). The dirt on headlamp lenses is a significant factor affecting the amount of light available on the road.

Degradation of Headlamps

Casual observance of headlamp lenses indicates that some can degrade rather quickly. This degradation results in a decrease in the luminous intensity from headlights, resulting in less illuminance on the road. Sealed beam headlamps have almost no degradation because of their glass lenses and because they do not admit moisture or dirt inside the unit. Modern headlamps made of hard plastic lenses suffer from yellowing, fogging, etc., which is caused by various factors like acid rain, condensation, and high heat. The amount of degradation also depends on the type of protective coating applied. A scratched beam can alter the beam pattern and sometimes increase the glare. Figure II.10 shows the difference between a degraded and a new headlamp lens.

The reduction in luminous intensity due to degraded headlamp lenses has not been considered in research pertaining to the design of sag vertical curves. Considering the rate at which modern headlamp lenses degrade, it might be necessary to incorporate a factor in the design formula that accounts for the degradation of lenses.



(a) Hazed and Yellowed Headlamp Lens (b) New Headlamp Lens

FIGURE II.10 Headlamp Lenses (*37*)

GEOMETRIC DESIGN CRITERIA FOR SAG VERTICAL CURVES

Geometric design standards provide guidance to engineers who design highways. They also aid in the development of safe and economic solutions, while meeting the requirements of highway users. The issue related to the relationship between crash risk and design guidelines has been seldom evaluated. Hauer (*41*), one of the few who examined this issue, states that many geometric design guidelines are not based on the frequency or severity of crashes. As a result the true relationship between design standards and safety is not well established. Although this issue is beyond the scope of this research, further work may be needed on this topic. For this thesis, the researcher based her study on the existing design concepts and did not evaluate the relationship between sag curve design criteria and crashes.

One requirement of these design guides is to provide adequate stopping sight distance (SSD) on the roadway. The SSD values specified in “A Policy of Geometric Design of Highways and Streets”, published by the American Association of State

Highway and Transportation Officials (AASHTO), also known as the Green Book, enables drivers to detect an object on the road and stop safely before hitting it (*42*). Horizontal and vertical curves on a roadway create restrictions to sight distance. If the design of these curves meets the criteria specified in the AASHTO Green Book, the required SSD should be available at every point along the curve. The importance of sight distance in the design of a highway was documented as early as 1914 in engineering textbooks (*43*). Design guides state the different criteria for determining the length of a sag vertical curve, of which the headlight sight distance is an important factor to be considered (*33, 34, 42*).

Headlight Sight Distance

For safe highway operations, a vehicle traveling at design speed should be provided with a sight distance sufficient for it to stop before reaching a vehicle or object in its path. AASHTO states, "The available sight distance on a roadway should be sufficiently long to enable a vehicle traveling at or near the design speed to stop before reaching a stationary object in its path" (*42*). For safe driving conditions, the length of a sag vertical curve should be designed to provide a headlight beam distance that is about the same as the minimum stopping sight distance. The importance of headlight sight distance in the design of sag curves was recognized and used in the design of the Pennsylvania Turnpike. The review of literature revealed that the Pennsylvania Turnpike used the first design charts (documented in 1940) to provide sight distance on sag curves (*44*). These design charts used a headlamp divergence angle of 1.0 degree to determine the length of sag curves. Later these design charts were used to develop formulas to calculate the length of sag curves. Considering headlight sight distance (S) as the ruling criteria, design formula to calculate the length of sag vertical curves were first published in 1944 (*45*). These equations have remained the same since then, except for the change in headlamp mounting height from 2.5 ft to 2.0 ft. Equations II.7 and II.11 represent the formulas used for calculating the length of sag curves for two conditions, S less than the length of the curve (L) and S greater than L. The value of S in these equations is equal to the stopping sight distance (which in turn depends on the speed). Headlight sight distance is the illuminated section of highway ahead of a vehicle on a sag vertical curve. It depends on the position of the headlights and the direction of the light beam. The following show the values commonly employed for calculation:

- Headlight height above the ground: 2.0 ft
- Light beam: 1.0 degree upward divergence from the longitudinal axis of the vehicle.

The length of sag vertical curves can be determined for the following two conditions based on the headlight sight distance.

<u>Case 1</u>

When S is less than L:

The length of the sag vertical curve is assumed to be greater than the headlight sight distance (which is about the same as the stopping sight distance). The equation for this condition is derived considering the location of the vehicle as shown in Figure II.11; at this point, the available sight distance is equal to the SSD. If the shape of the sag curve is assumed to be a parabola, with an equation $y = ax^2$, the coordinates of point 'O' are (*45*):

$$y = h + S \tan \alpha \qquad \text{(II.2)}$$

$$x = S \qquad \text{(II.3)}$$

Substitute these values in the equation $y = ax^2$ to get 'a,'

$$a = \frac{h + S \tan \alpha}{S^2} \qquad \text{(II.4)}$$

$$y = \frac{h + S \tan \alpha}{S^2} x^2 \qquad \text{(II.5)}$$

The rate of change of tangent per foot is the second derivative of Equation 11.5.

$$A = \frac{d^2 y}{dx^2} L = 2L\left(\frac{h + S \tan \alpha^{\circ}}{S^2}\right) \qquad \text{(II.6)}$$

Then, the length of the curve is give by the equation:

$$L = \frac{AS^2}{200[h + S(\tan \alpha)]} \qquad \text{(II.7)}$$

where:

L: Length of sag vertical curve (ft)

S: Headlight beam distance, taken equal to the SSD (ft)

A: Algebraic difference in grades (percent)

h: Headlight height (ft)

α: Upward divergence angle (degree)

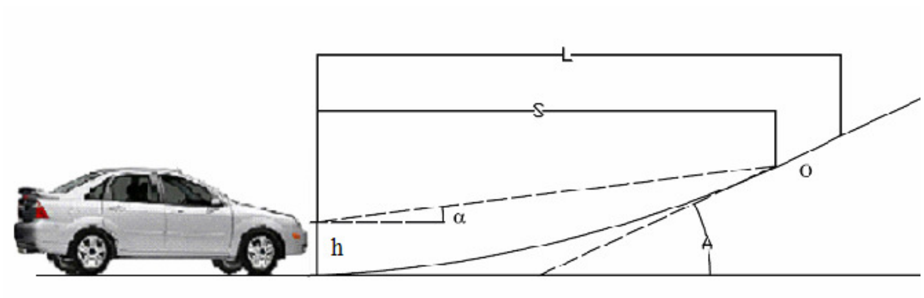


FIGURE II.11 Sag Curve for S<L (*45*)

<u>Case 2</u>

When S is greater than L:

The length of the sag vertical curve is assumed to be less than the headlight sight distance (which is about the same as the stopping sight distance). The equation for this condition is derived considering the position of the vehicle as shown in Figure II.12; at this point the available sight distance is equal to the SSD (*45*).

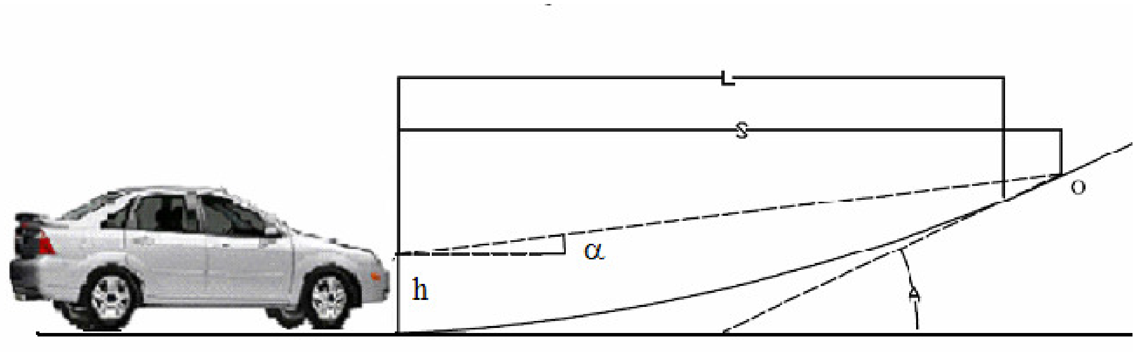


FIGURE II.12 Sag Curve for S>L Condition (*45*)

If the shape of the sag curve is assumed to be a parabola, the y-coordinate of point 'O' can be expressed as (*45*):

$$y = h + S \tan \alpha \qquad \text{(II.8)}$$

$$y = \frac{AL}{2} + (S - L)A \tag{II.9}$$

Equating the above two equations:

$$h + S\tan\alpha = (S - \frac{L}{2})A \tag{II.10}$$

$$L = 2S - \frac{200[h + S(\tan\alpha)]}{A} \tag{II.11}$$

where:

L: Length of sag vertical curve (ft)

S: Headlight beam distance, taken equal to the SSD (ft)

A: Algebraic difference in grades (percent)

h: Headlight height (ft)

α: Upward divergence angle (degree)

Passenger Comfort

Since the gravitational and centripetal forces act in different directions while traversing a sag curve, a change in the vertical grade has an impact on the comfort of the passengers. When centripetal acceleration is less than 1 ft/s^2, riding is comfortable. The formula for determining the length of a sag curve based on comfort criteria is shown in Equation II.12 (*42*).

$$L = \frac{AV^2}{46.5} \tag{II.12}$$

Where, V: Design speed, mph

The length of a sag curve determined from the above formula is about half the length determined using the headlight sight distance criteria under normal conditions. Thus, the length of a sag curve is generally determined using the headlight sight distance criteria (*42*).

Drainage

The formulas discussed so far give the minimum length of a sag curve to be used in design. However, the length of sag curves determined using drainage criteria give the maximum length to be used in the design. Drainage criterion affects the design of sag vertical curves where curbed sections are employed. To satisfy the drainage requirements, a minimum grade of 0.3 percent should be provided within 50 ft of the level point on the curve (*42*).

Esthetics

For small and intermediate values of 'A', the minimum curve length is determined using a rule of thumb. The rule of thumb uses 100A as the minimum curve length to satisfy the appearance criteria. Longer curves usually improve appearance and are appropriate for use on high type highways (*42*).

Use of Headlight Sight Distance for Design

Design guides recommend the use of headlight sight distance criteria in determining the length of sag vertical curves for general use. An examination of different criteria shows that headlight sight distance is the most logical criteria to be used for design purposes. However, drainage conditions should be checked when using a K value greater than 167. ‘K’ is the rate of vertical curvature, defined as the length of curve per percent algebraic difference in grades.

The 1954 AASHO Blue Book (*33*) is the first national design guide in which the sag curve formulas were used. Sealed beam headlamps were commonly used on vehicles in that period. Recent studies show that there has been a considerable change in headlamps and their beam pattern (*4, 5*). A review of the literature shows that the formulas used for the design of sag curves have not been revised over time; neither have any studies been performed to examine their adequacy in relation to the changing headlamp patterns. These formulas may require revisions when considering the modern fleet of vehicles using the highways.

CHAPTER III

DATA ANALYSIS FOR THEORETICAL DATA

This chapter describes the theoretical analysis performed to determine the illuminance at specific points on a sag curve. The first section gives a description of the headlamp light output data, which was used for the analysis. The next section details the procedure used to determine specific points at which illuminance is required and a description of the analysis performed. The final section presents the results of the analysis.

PHOTOMETRIC DATA

Illuminance at different points on a roadway depends on the luminous intensity produced by a vehicle's headlamps. Luminous intensity values at regular horizontal and vertical angles on a headlamp are available in photometric data or light output data files. Based on the position of the vehicle on the road and the coordinates of the point on the road where the illuminance is required the horizontal and vertical headlight angles are calculated.

The horizontal angles, H_h are calculated using Equation III.1.

$$H_h = \tan^{-1}\left(\frac{(\frac{w}{2} - d \pm \frac{l}{2})}{S}\right) \qquad \text{(III.1)}$$

where,

w: Width of the road (12 ft)

d: Distance of observation point from the right edge line (ft)

l: Headlamp separation (ft); $+\frac{l}{2}$: for left headlamp; $-\frac{l}{2}$: for right headlamp

S: Headlight sight distance (ft)

The vertical headlamp angle, H_v is the headlamp upward divergence angle α. The researcher used this information to obtain luminous intensity values from photometric data tables at the required points on a headlamp. Table III.1 represents a sample array of photometric data for a CARTS headlamp at different horizontal and vertical angles. The top row consists of horizontal headlight angles (H_h) at 0.5 degree increments and the first column consists of vertical headlight angles (H_v) at 0.5 degree intervals. The luminous intensity values are in candelas. When the exact (H_h, H_v) was not available in the photometric data, the researcher interpolated the surrounding values using Equation III.2 to obtain the luminous intensity at the required point.

The interpolation procedure used is as follows:

- Surround H_h and H_v by four consecutive angles, $a<b\leq H_h\leq c<d$, $e<f\leq H_v\leq g<h$.
- Take $H_h = a$; surround H_v by four consecutive angles $e<f\leq H_v\leq g<h$. Using the luminous intensity values at (a, e), (a, f), (a, g), and (a, h) and Equation III.2 determine luminous intensity at (a, Hv).
- Similarly, determine luminous intensities at (b, H_v), (c, H_v), and (d, H_v).

- Using these four values, calculate the luminous intensity at (H_h, H_v) using Equation III.2 (*46*). The researcher developed a spreadsheet to calculate the luminous intensity values at required points.

$$f(x) = \max\left\{\left(\frac{A-B-C+D}{6}\right)\left(\frac{x-b}{\Delta}\right)^2 - \left(\frac{-A-5B+7C-D}{6}\right)\left(\frac{x-b}{\Delta}\right) + B, 0.8\left[(C-B)\left(\frac{x-b}{\Delta}\right) + B\right]\right\}$$

(III.2)

where:

a, b, c, d are four consecutive angles having photometric data such that, a<b<x<c<d

Δ: d-c = c-b = b-a

f(a) = A, f(b) = B, f(c) = C, f(d) = D

TABLE III.1 Luminous Intensity (cd) Values for a Sealed Beam Headlamp

		Horizontal Headlight Angles, H_h (degree)								
		-2	**-1.5**	**-1**	**-0.5**	**0**	**0.5**	**1**	**1.5**	**2**
Vertical Headlight Angles, H_v (degree)	**3**	262	294	311	325	336	360	369	375	379
	2.5	325	346	351	374	405	422	453	436	441
	2	387	408	419	443	507	540	544	574	608
	1.5	464	501	558	594	651	742	797	878	821
	1	533	613	665	752	813	924	1032	1090	1091
	0.5	644	761	876	1060	1099	1297	1682	1771	1688
	0	961	1114	1286	1793	2310	3010	3640	4400	4440
	-0.5	1679	2050	2500	3470	5050	7350	9370	10200	11920
	-1	2900	3320	4190	6180	8960	12850	16370	17490	19130
	-1.5	4560	4810	6740	9060	12640	15300	18320	20300	21500
	-2	5040	6140	7480	9410	11850	13850	16590	19000	19780
	-2.5	5780	6600	7030	8390	9790	11070	11960	13140	13790
	-3	5200	5690	6440	6950	7310	7970	8080	8820	9650

Headlamp photometric data are available from laboratories that measure automobile headlamps. These laboratories use a goniometer for their measurements.

Figure III.1 shows a typical laboratory setup, with a headlamp mounted on a goniometer table and the light beam projected onto the white wall; the sensors of the illuminance meter (used to measure the illuminance) are located behind the white wall. The headlamp to be measured is removed from the vehicle and mounted on a bracket that holds it in position and allows it to be rotated precisely as required. The lamp is then rotated at required horizontal and vertical increments to present the required angle to the illuminance meter. This is equivalent to keeping the headlamp stationary and moving the illuminance meter at required increments (*47*). The data for each of the measured points are arranged as shown in Table III.1. The researcher obtained the photometric data required for this research effort from various sources regularly involved with headlamp testing.

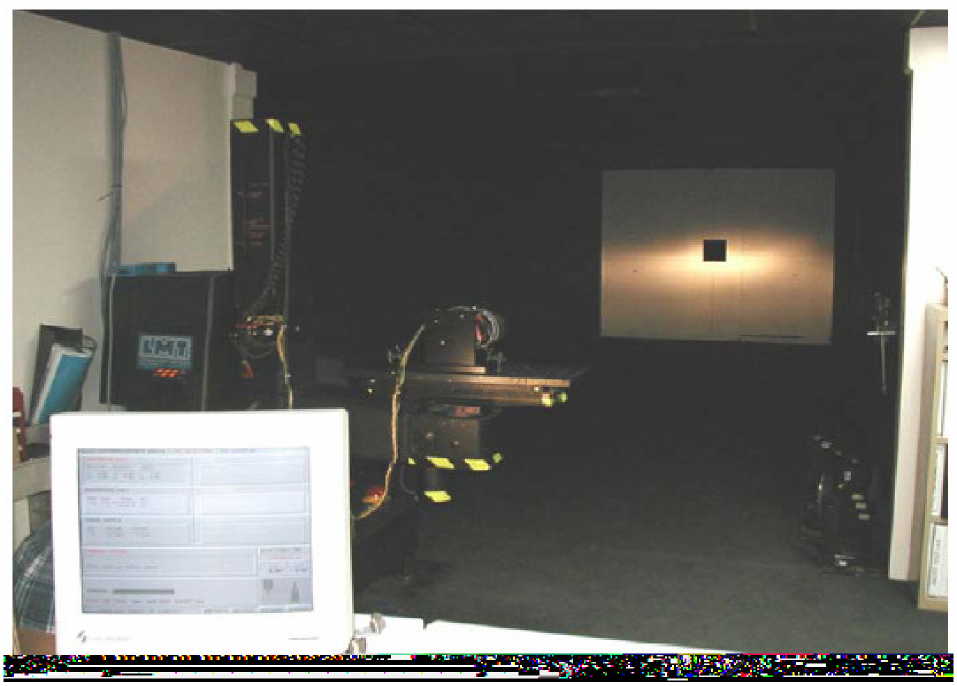


FIGURE III.1 Laboratory Setup Showing Headlamp Mounted on the Goniometer Table and the Beam Pattern Being Projected onto a White Wall (*47*)

PROCEDURE FOR DATA ANALYSIS

Identification of critical points on a sag curve was the first step of this research.

- For a driver to stop safely after identifying an object, he should be provided with sight distance at least equal to the SSD at every point on the road.
- This condition is satisfied in sag curves by equating the headlamp sight distance (S) to the SSD.
- A change in illuminance at a distance equal to SSD, will significantly affect the visibility of an object.
- Based on this idea, for the analysis, the researcher calculated the illuminance values at a distance equal to SSD across the width of the road (at 2 ft intervals) with the vehicle located on the start of the curve. The plan view in Figure III.2 shows the points of interest where the illuminance values are required.

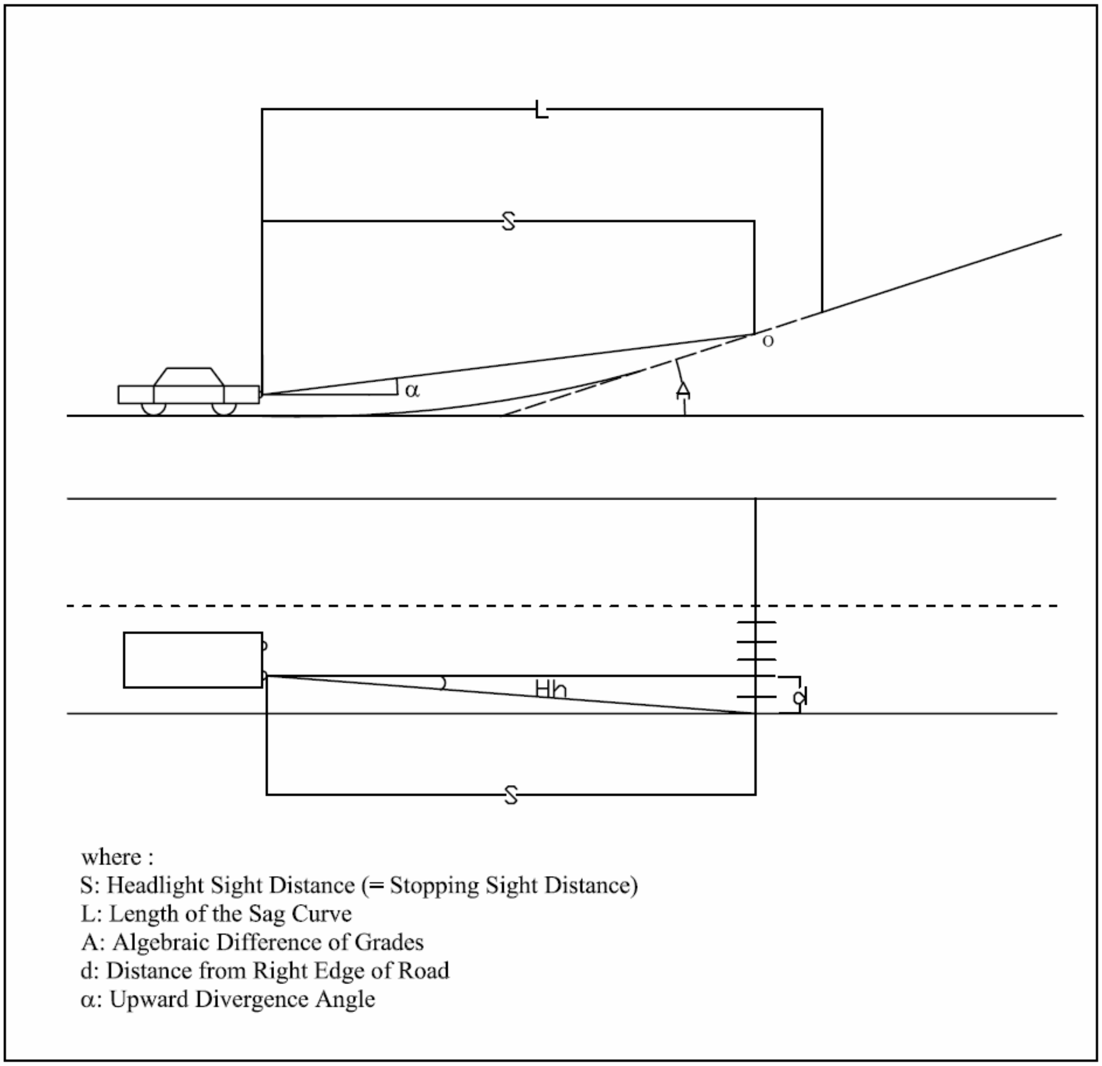


FIGURE III.2 Profile and Plan View of a Sag Curve

The second step of the research was to identify the specific sag curves on which the illuminance values are to be determined.

- The design of sag curves depends on different A, L, and SSD values. A combination of these parameters gives several different curves.

- The SSD depends on the design speed of the highway under consideration. For the present study, the researcher considered the speeds and corresponding SSDs shown in Table III.2. At lower design speeds, the SSD would be at a shorter distance, and the light available might be sufficient to provide required visibility (though the illuminance values provided by sealed beam and modern headlamps could vary).

TABLE III.2 Stopping Sight Distances Corresponding to the Different Design Speeds (*42*)

Design Speed (mph)	Stopping Sight Distance (ft)
60	570
65	645
70	730

- The objective of this study is to identify the change in the amount of light reaching the road when using different headlamps. This objective can be achieved by using any sag curve having different 'A' values and different conditions of S<L or S>L. Keeping this in mind, the researcher chose three sag curves for the study. The following describe the three sag curves used in the research:

  Curve 1: Speed 60 mph; SSD: 570 ft; A: 6 percent; L: 816 ft; condition S<L. Location of vehicle: Start of the curve.

  Curve 2: Speed 65 mph; SSD: 645 ft; A: 6 percent; L: 942 ft; condition S<L. Location of vehicle: Start of the curve.

Curve 3: Speed 70 mph; SSD: 730 ft; A: 4 percent; L: 724 ft; condition S>L.

Location of vehicle: Start of the curve.

The next step was to determine the illuminance values at the required points on the sag curves using photometric data from different headlamps.

- The angles for each headlamp (left and right) to the different points on the road are different. These angles depend on the horizontal and vertical (H/V) positions of each point on the road relative to the headlamp. These photometric angles are used to determine the luminous intensity values at the corresponding points on the headlamp. Luminous intensity values are not measured at all the points in the laboratory. To obtain the luminous intensity value of an unmeasured point, the researcher used interpolation of the nearby available values.
- The vertical angles, H_v for this study, consisted of 1.0 degree and 0.85 degree angles. The researcher used the 1.0 degree angle as it represents the headlight beam angle in the sag curve design formulas. The researcher performed a preliminary analysis using different H_v angles for UMTRI 2004 to determine an angle that would give illuminance values comparable to the CARTS headlamps at a H_v angle of 1.0 degree. The researcher determined the average illuminance values across the width of the road at a distance of 570 ft using different H_v angles for UMTRI 2004 headlamps. Table III.3 shows a comparison of these illuminance values to the CARTS values at H_v of 1.0 degree. From the table it is observed that using a H_v angle of 0.9 degrees for UMTRI 2004 gives less illuminance when compared to CARTS at 1 degree and using a H_v angle of 0.8

degrees gives more illuminance. An angle of 0.85 degrees for UMTRI 2004 will give comparable illuminance values to the CARTS headlamps. Based on these preliminary results, the researcher decided to use a H_v angle of 0.85 degrees in the analysis.

TABLE III.3 Illuminance Comparison between CARTS and UMTRI 2004 Using Different H_v Values

Headlamp	Illuminance (lx)	% Change
CARTS 1.0º	0.055	-
UMTRI 2004-0.80º	0.063	14.5
UMTRI 2004-0.85º	0.056	1.8
UMTRI 2004-0.90º	0.049	-10.9

- The researcher calculated the horizontal angles (H_h) for different stopping sight distances at points across the width of the road, 2 ft apart.
- The angles depend on the distance between the left and right headlamps. For the theoretical data analysis, the researcher used the headlamp separation distance of the UMTRI car. The dimensions of the UMTRI car represent a passenger sedan. The researcher chose the UMTRI car for uniformity and simplicity. Since different vehicles use the highways, it is impractical to make recommendations and changes to the design formula based on vehicle type. Also, readings obtained by affixing different headlamps to the same car will give uniform comparison of illuminance values (i.e. all else remaining same, the illuminance

values are directly compared). The following are the dimensions of the UMTRI car:

Distance between headlamps: 3.67 ft

The researcher developed a spreadsheet to calculate the illuminance values at the required points. The headlight intensity file and the coordinates of the point on the road serve as input for the spreadsheet. Equation III.3 shows the formula used for calculating the illuminance values.

$$E = \frac{I * 10.764}{\left(\frac{S}{\cos(\alpha)}\right)^2} \qquad \text{(III.3)}$$

where:

E: Illuminance (lx)

I: Luminous intensity (cd)

S: Horizontal distance (ft)

α: Headlight upward divergence angle (degree)

The researcher calculated the illuminance values independently for the left and right headlamps. The total illuminance at a point is the sum of these values.

DATA ANALYSIS AND COMPARISON OF ILLUMINANCE VALUES

The researcher performed the data analysis for the chosen three curves using the developed spreadsheet. Next, she compared the illuminance values for headlamp divergence angles of 1.0 degree and 0.85 degree for each curve. The headlamps consisted of sealed beam and modern headlamps. Tables III.4 and III.5 summarize the description of the headlamps used in the analysis. The 92×150, CARTS, and 2A1 are classified as old model headlamps. The 92×150 is a low beam, type LF rectangular sealed beam headlamp with a dimension of 92×150 mm; the 2A1 is a low beam rectangular headlamp, with a dimension of 100×165 mm. CARTS represents the 50th percentile low beam headlamp data obtained from 26 U.S. headlamps consisting of 1985-1990 vehicles. The UMTRI 1997, 2000, 2004, and the Ford Taurus 2003 come under the classification of modern headlamps. The UMTRI 2000 isocandela profiles included a sample of visually optically aimable (VOA) headlamps not present in the UMTRI 1997 profiles. A study performed by UMTRI showed that VOA headlamps provide comparatively less light for night time visibility. Ford Taurus 2003 used in the analysis sports VOR headlamps with reflector optics.

TABLE III.4 Old Model Headlamp Description

	Sealed Beam	**CARTS 1985-1990**	**Sealed Beam**
Shape	Rectangular	Composite	Rectangular
Size	92×150	Composite	100×165
Type	LF	Composite	A

TABLE III.5 Modern Headlamp Description

	UMTRI 1997	**UMTRI 2000**	**Taurus 2003**	**UMTRI 2004**
Shape	Composite	Composite	-	Composite
Type	Composite	Composite (included VOA)	VOR	Composite

Curve 1

The researcher used a design speed 60 mph and corresponding SSD of 570 ft for Curve 1. An 'A' value of 6 percent and 'L' of 816 ft for S<L condition was used. The vehicle was located at the start of the curve.

For these parameters the researcher calculated illuminance values at points across the width of the road using different headlamps. Table III.6 and Figure III.3 show these values for a headlamp divergence angle of 1.0 degree. Table III.7 shows the percentage difference in illuminance for CARTS and UMTRI 2004, and for CARTS and UMTRI 2000 headlamps at a H_v angle of 1 degree.

TABLE III.6 Illuminance Values from Different Headlamps for Curve 1 and H_v: 1.0 degree

Distance to the left of right edge line, d (feet)	Total Illuminance Values (lx)						
	Sealed Beam Headlamps			Modern Headlamps			
	92×150	CARTS	2A1	UMTRI 1997	UMTRI 2000	Taurus 2003	UMTRI 2004
12	0.0539	0.0485	0.0390	0.0329	0.0330	0.0414	0.0396
10	0.0560	0.0504	0.0411	0.0347	0.0334	0.0430	0.0403
8	0.0584	0.0523	0.0432	0.0368	0.0339	0.0443	0.0408
6	0.0613	0.0544	0.0453	0.0391	0.0344	0.0456	0.0405
4	0.0646	0.0567	0.0473	0.0413	0.0350	0.0468	0.0401
2	0.0689	0.0597	0.0489	0.0432	0.0356	0.0477	0.0399
0	0.0740	0.0627	0.0500	0.0447	0.0362	0.0483	0.0405
Average	0.0624	0.0550	0.0450	0.0390	0.0345	0.0453	0.0402

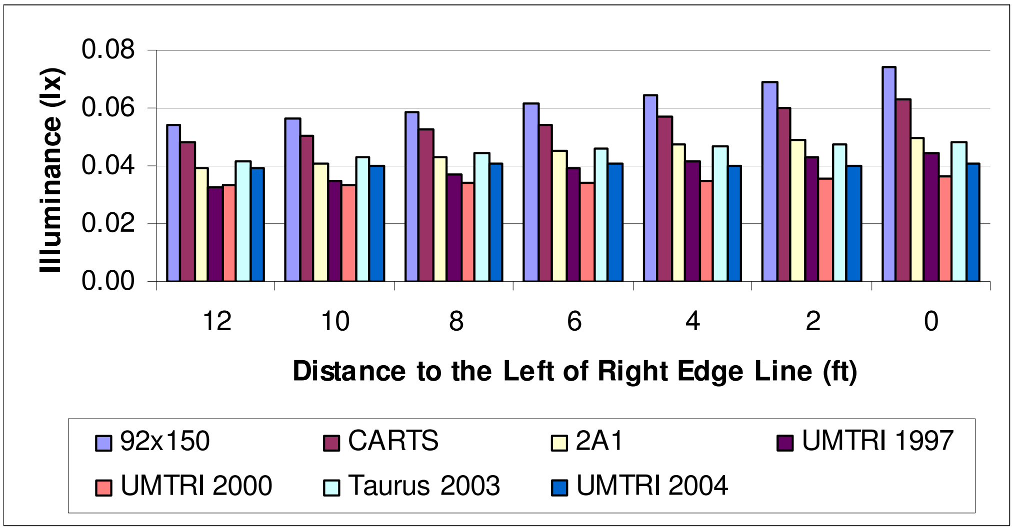


FIGURE III.3 Illuminance Values for Different Headlamps for Curve 1 and H_v: 1.0 degree

TABLE III.7 Comparison of Illuminance (lx) Values for Curve 1 and H_v: 1.0 degree

Distance to the left of right edge line, d (ft)	Illuminance (lx)			% Change	
	CARTS	UMTRI 2004	UMTRI 2000	CARTS-UMTRI 2004	CARTS-UMTRI 2000
12	0.0485	0.0396	0.0330	-18.35	-31.96
10	0.0504	0.0403	0.0334	-20.04	-33.73
8	0.0523	0.0408	0.0339	-21.99	-35.18
6	0.0544	0.0405	0.0344	-25.55	-36.76
4	0.0567	0.0401	0.0350	-29.28	-38.27
2	0.0597	0.0399	0.0356	-33.17	-40.37
0	0.0627	0.0405	0.0362	-35.41	-42.26
Average	0.0550	0.0402	0.0345	-26.26	-36.93

Table III.8 shows the difference in illuminance values between CARTS headlamps at a H_v angle of 1.0 degree and UMTRI 2004 headlamps at a H_v angle of 0.85

degrees. An examination of these values shows that the illuminance values of UMTRI 2004 headlamps at 0.85 degrees are closer to the illuminance values of CARTS headlamps at 1.0 degree.

TABLE III.8 Comparison of Illuminance (lx) Values between CARTS at H_v: 1.0 degree and UMTRI 2004 at H_v: 0.85 degree for Curve 1

Distance to the left of right edge line, d (ft)	Illuminance (lx)		% Change
	CARTS-1.0°	UMTRI 2004-0.85°	
12	0.0485	0.0481	-0.82
10	0.0504	0.0514	1.98
8	0.0523	0.0545	4.21
6	0.0544	0.0567	4.23
4	0.0567	0.0584	3.00
2	0.0597	0.0595	-0.34
0	0.0627	0.0606	-3.35
Average	0.0550	0.0556	1.27

Curve 2

The researcher used a design speed 65 mph and corresponding SSD of 645 ft for Curve 2. An 'A' value of 6 percent and 'L' of 942 ft for S<L condition was used. The vehicle was located at the start of the curve.

For these parameters the researcher calculated illuminance values at points across the width of the road using different headlamps. These values are represented in Table III.9 and Figure III.4 for a headlamp divergence angle of 1.0 degree. Table III.10 shows the percentage difference in illuminance for CARTS and UMTRI 2004, and for CARTS and UMTRI 2000 headlamps at a H_v angle of 1 degree.

TABLE III.9 Illuminance Values for Different Headlamps for Curve 2 and H_v: 1.0 degree

Distance to the left of right edge line, d (ft)	Total Illuminance Values (lx)						
	Sealed Beam Headlamps			Modern Headlamps			
	92×150	CARTS	2A1	UMTRI 1997	UMTRI 2000	Taurus 2003	UMTRI 2004
12	0.0426	0.0384	0.0310	0.0261	0.0259	0.0328	0.0311
10	0.0441	0.0398	0.0324	0.0274	0.0262	0.0338	0.0317
8	0.0458	0.0409	0.0339	0.0289	0.0265	0.0347	0.0319
6	0.0478	0.0424	0.0354	0.0306	0.0269	0.0356	0.0317
4	0.0501	0.0440	0.0368	0.0321	0.0272	0.0364	0.0314
2	0.0529	0.0461	0.0379	0.0334	0.0277	0.0371	0.0309
0	0.0562	0.0481	0.0388	0.0345	0.0281	0.0376	0.0314
Average	0.0485	0.0428	0.0352	0.0304	0.0269	0.0354	0.0314

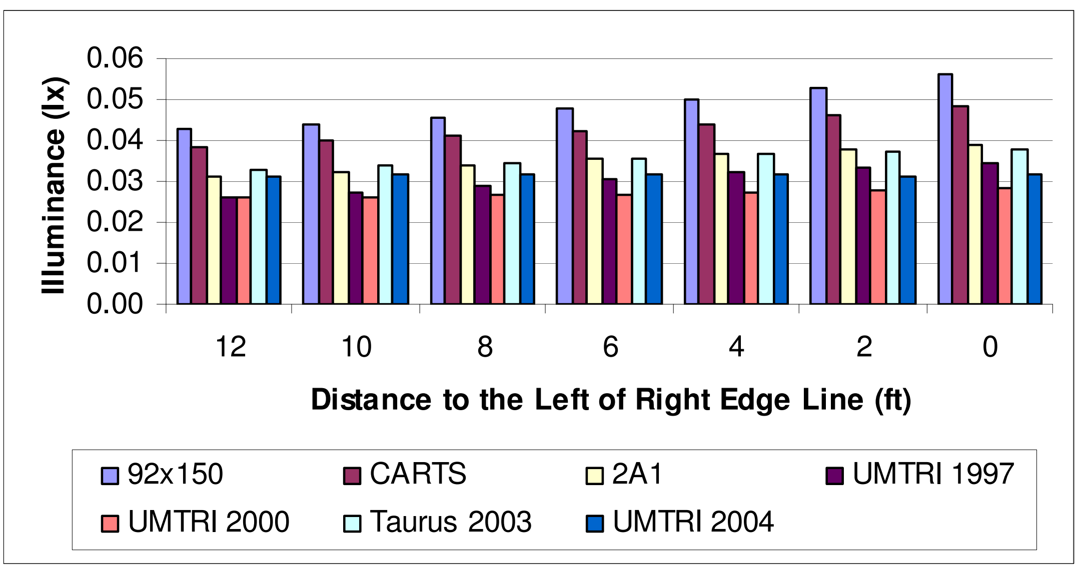


FIGURE III.4 Illuminance Values from Different Headlamps for Curve 2 and H_v: 1.0 degree

TABLE III.10 Comparison of Illuminance (lx) Values for Curve 2 and H_v: 1.0 degree

Distance to the left of right edge line, d (ft)	Illuminance (lx)			% Change	
	CARTS	UMTRI 2004	UMTRI 2000	CARTS-UMTRI 2004	CARTS-UMTRI 2000
12	0.0384	0.0311	0.0259	-19.01	-32.55
10	0.0398	0.0317	0.0262	-20.35	-34.17
8	0.0409	0.0319	0.0265	-22.00	-35.21
6	0.0424	0.0317	0.0269	-25.24	-36.56
4	0.0440	0.0314	0.0272	-28.64	-38.18
2	0.0461	0.0309	0.0277	-32.97	-39.91
0	0.0481	0.0314	0.0281	-34.72	-41.58
Average	0.0428	0.0314	0.0269	-26.13	-36.88

Table III.11 shows the difference in illuminance values between CARTS headlamps at a H_v angle of 1.0 degree and UMTRI 2004 headlamps at a H_v angle of 0.85 degrees. An examination of these values shows that the illuminance values of UMTRI 2004 headlamps at 0.85 degrees are closer to the illuminance values of CARTS headlamps at 1.0 degree.

TABLE III. 11 Comparison of Illuminance (lx) Values between CARTS at H_v: 1.0 degree and UMTRI 2004 at H_v: 0.85 degree for Curve 2

Distance to the left of right edge line, d (ft)	Illuminance (lx)		% Change
	CARTS-1.0°	UMTRI 2004-0.85°	
12	0.0384	0.0385	0.26
10	0.0398	0.0409	2.76
8	0.0409	0.0429	4.89
6	0.0424	0.0444	4.72
4	0.0440	0.0455	3.41
2	0.0461	0.0462	0.22
0	0.0481	0.0471	-2.08
Average	0.0428	0.0436	2.03

Curve 3

The researcher used a design speed 70 mph and corresponding SSD of 730 ft for Curve 3. An ‘A’ value of 4 percent and ‘L’ of 724 ft for S>L condition was used. The vehicle was located at the start of the curve.

For theses parameters, as in the case for Curves 1 and 2, the researcher calculated illuminance values at points across the width of the road using different headlamps. These values are represented in Table III.12 and Figure III.5 for a headlamp divergence angle of 1.0 degree. Table III.13 shows the percentage difference in illuminance for CARTS and UMTRI 2004 and for CARTS and UMTRI 2000 headlamps at a H_v angle of 1 degree.

TABLE III.12 Illuminance Values for Different Headlamps for Curve 3 and H_v: 1.0 degree

Distance to the left of right edge line, d (ft)	Total Illuminance Values (lux)						
	Sealed Beam Headlamps			Modern Headlamps			
	92×150	CARTS	2A1	UMTRI 1997	UMTRI 2000	Taurus 2003	UMTRI 2004
12	0.0337	0.0304	0.0245	0.0207	0.0204	0.0259	0.0245
10	0.0347	0.0313	0.0255	0.0216	0.0206	0.0266	0.0248
8	0.0359	0.0320	0.0266	0.0227	0.0207	0.0272	0.0249
6	0.0373	0.0330	0.0276	0.0238	0.0210	0.0278	0.0248
4	0.0388	0.0342	0.0286	0.0249	0.0213	0.0284	0.0246
2	0.0407	0.0357	0.0295	0.0259	0.0215	0.0288	0.0241
0	0.0429	0.0370	0.0301	0.0267	0.0218	0.0293	0.0243
Average	0.0377	0.0334	0.0275	0.0238	0.0210	0.0277	0.0246

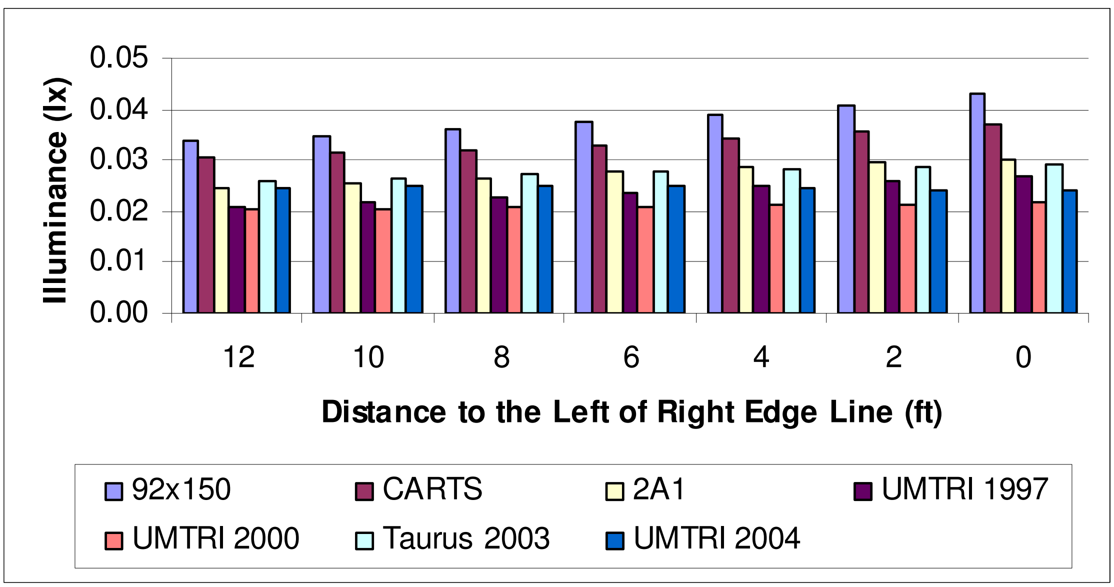


FIGURE III.5 Illuminance Values from Different Headlamps for Curve 3 and H_v: 1.0 degree

TABLE III.13 Comparison of Illuminance (lx) Values for Curve 3 and Hv: 1.0 degree

Distance to the left of right edge line, d (ft)	Illuminance (lx)			% Change	
	CARTS	UMTRI 2004	UMTRI 2000	CARTS-UMTRI 2004	CARTS-UMTRI 2000
12	0.0304	0.0245	0.0204	-19.41	-32.89
10	0.0313	0.0248	0.0206	-20.77	-34.19
8	0.0320	0.0249	0.0207	-22.19	-35.31
6	0.0330	0.0248	0.0210	-24.85	-36.36
4	0.0342	0.0246	0.0213	-28.07	-37.72
2	0.0357	0.0241	0.0215	-32.49	-39.78
0	0.0370	0.0243	0.0218	-34.32	-41.08
Average	0.0334	0.0246	0.0210	-26.01	-36.76

Table III.14 shows the difference in illuminance values between CARTS headlamps at a H_v angle of 1.0 degree and UMTRI 2004 headlamps at a H_v angle of 0.85 degrees. An examination of these values shows that the illuminance values of UMTRI 2004 headlamps at 0.85 degrees are closer to the illuminance values of CARTS headlamps at 1.0 degree.

TABLE III.14 Comparison of Illuminance (lx) values for CARTS at H_v: 1.0 degree and UMTRI 2004 at H_v: 0.85 degree for Curve 3

Distance to the left of right edge line, d (ft)	Illuminance (lx)		% Change
	CARTS-1.0º	UMTRI 2004-0.85°	
12	0.0304	0.0307	0.99
10	0.0313	0.0323	3.19
8	0.0320	0.0336	5.00
6	0.0330	0.0346	4.85
4	0.0342	0.0355	3.80
2	0.0357	0.0360	0.84
0	0.0370	0.0365	-1.35
Average	0.0334	0.0342	2.4743

To examine the change in beam pattern in modern headlamps compared to sealed beam headlamps, the researcher calculated the percentage change in the amount of light produced by different headlamps at specific points. These comparison tables show that the illuminance values differ significantly for the sealed beam headlamps and the modern headlamps at a H_v angle of 1.0 degree. The use of a H_v angle of 0.85 degree for modern headlamps, gives illuminance values more comparable to those calculated using 1.0 degree H_v angle for sealed beam headlamps.

The 1.0 degree H_v angle used in the formula has a significant impact on determining the visible length of roadway. For example, for a curve of length of 1086 ft and A: 6 percent, Table III.15 shows the variation of S depending on the α angle used in the equation: $L = \frac{AS^2}{200[h + S(\tan\alpha)]}$. This calculation shows that a change of 0.1 degree in the H_v angle results in a significant change in the available sight distance. By using

0.85 degree for the value of α in the formula, an 'S' value of 649 ft is obtained. This represents about an 11 percent reduction in the available sight distance.

TABLE III.15 Sight Distance Corresponding to Different α Values

α (degree)	**S (ft)**
1.0	730.9
0.9	675.8
0.8	621.9
0.7	569.4
0.6	518.7
0.5	470.0

Similarly, when all the parameters remain the same, an increase in the length of the curve will provide the required sight distance. The curves used in the analysis of this chapter will have the lengths shown in Table III.16 when using an H_v angle of 0.85 degrees. Even when using a different α value in the design formula, the same design procedures can be followed.

TABLE III.16 Length of Curve for Different Values of α

	Length of Curve (ft)		
	Curve 1	**Curve 2**	**Curve 3**
α :1.0 degree	816	942	724
α : 0.85 degree	932	1079	831
% Increase	14.0	14.5	14.8

For Curve 3, the design condition is S>L when using an α of 1 degree. This condition changes to S<L when an α of 0.85 degree is used in the formula. However, for the S>L condition, AASHTO does not recommend the use of design charts and ‘K’ value for determining the length of the curve. A minimum curve length equal to 0.6 times the design speed is usually adopted for the S>L condition (*42*). So, the change in illuminance will not impact the design of these sag curves.

CHAPTER IV

DATA ANALYSIS FOR FIELD STUDY

This chapter summarizes the data collection effort conducted in the field to measure illuminance values at different points using different headlamps. These measurements help validate the theoretical calculations in Chapter III. The researcher compared the field and theoretical illuminance to understand how field conditions impact illuminance values. The first section of this chapter describes the data collection procedure in the field. The next section consists of the data analysis, results, and comparison of field illuminance values to the theoretical values.

FIELD PROCEDURE

Field measurements serve to validate theoretical calculations. The researcher conducted a field study to observe how the illuminance values from different headlamps vary in the field and to see how they compare to the theoretical values. The researcher conducted the field study with a small sample size of vehicles.

For the field study the researcher simulated conditions similar to a sag curve by developing a special measuring screen at the Texas A&M University's Riverside Campus. Riverside Campus is a research and training facility where it is possible to test vehicles under partially controlled conditions. The researcher tested one vehicle at a time in darkness (turned off external artificial lighting). The researcher measured illuminance values at the predetermined positions using this setup and a Minolta T12 illuminance meter with remote photometer sensors. The light meter operated on AC current throughout the test period.

Measurement Points

To provide a comparison to the calculated theoretical values, the researcher measured the illuminance values for the same sag curves used for the theoretical analysis. Illuminance values were needed at distances of 570 ft, 645 ft, and 730 ft which represent SSDs corresponding to speeds of 60, 65, and 70 mph respectively. The Minolta T2 illuminance meter used for the measurements was not sensitive enough to get reliable readings at the distances used in the theoretical study. Keeping this in mind, the researcher took corresponding measurements at shorter distances. To determine the observation points corresponding to a distance of 570 ft at shorter distances, the researcher followed the steps outlined below:

- To obtain accurate measurements, the researcher measured illuminance corresponding to 570 ft at three different distances. The researcher took measurements at 125 ft, 250 ft, and 500 ft.
- The researcher calculated the horizontal headlamp angles for a distance of 570 ft and points at 2 ft intervals across the width of the road.
- Using these angles, the researcher calculated the corresponding horizontal points at 125 ft, 250 ft, and 500 ft.
- The vertical position of the points depends on the distance at which the measurements are taken and the headlamp divergence angle, i.e., 1.0 degree and

0.5 degree for this study. The 1.0 degree used for the measurements represents the α value used in the design formula of sag vertical curves. Measurements at 0.5 degree will aid the researcher in comparing illuminance values of the Taurus at this angle to those of the light truck at 1.0 degree.

Test Vehicles

For the study, the researcher used four vehicles. They consisted of two Chevrolet 2500 light trucks, of the year models 1995 and 1997, with sealed beam headlamps (130×190, type 2B1); and two Ford Taurus cars, of the model year 2003, with modern headlamps (VOR headlamps with reflector optics). Figure IV.1 (a) shows the picture of Ford Taurus and (b) shows the Chevrolet 2500 light truck. The researcher took physical measurements of the vehicles in inches. The researcher measured the distance from the ground to the center of the vehicle's headlamps as the headlamp height. She next measured the distance from the center of the vehicle to the center of a headlamp and multiplied this value by two to obtain the measurement for headlamp separation. Table IV.1 shows the physical measurements for the two types of vehicles.

TABLE IV.1 Physical Characteristics of Test Vehicles

	Chevrolet 2500 Light Trucks	**Ford Taurus**
Headlamp Height (in)	36	26.5
Headlamp Separation (in)	57	46

(a) Ford Taurus 2003 (b) Chevrolet 2500 Light Truck

FIGURE IV.1 Vehicles Used or Field Measurements

Headlamp Aiming

The researcher adjusted the headlamp aim for all test vehicles before taking any measurements. The researcher aimed the headlamps as closely as possible in the absence of a mechanical headlamp aiming device. The researcher followed the aiming procedure appropriate for each vehicle after cleaning each headlamp.

For the Taurus cars, the researcher followed the procedure described in the owner's manual to aim the headlamps. The researcher did not correct the horizontal aim as it was non-adjustable and the user's manual mentioned that it did not require adjustment. The following is the procedure to correct the vertical headlamp aim:

- Park the vehicle on level ground, 25 ft away from a vertical wall.
- Measure the headlamp height and use masking tape to mark a corresponding horizontal reference line on the wall.
- Turn on the low beam headlamps, and cover one of the headlamps.

- Open the hood and turn the vertical adjuster until the top of the high intensity portion of light touches the horizontal line.
- Repeat the same procedure with the other headlamp.

The researcher corrected the vertical aim of the Taurus headlamps by following the above procedure for both the cars. Figure IV.2 (a) shows the adjustment of the vertical aiming screw, and (b) shows the high intensity light beam touching the masking tape.

(a) Adjustment of the Vertical Aiming Screw

(b) High Intensity Beam Touching the Masking Tape

FIGURE IV.2 Headlamp Aiming

The following is the procedure to correct the headlamp aim of light trucks having sealed beam headlamps:

- Park the vehicle on level ground, 25 ft away from a vertical wall.

- Measure the headlamp height, and use masking tape to mark a corresponding horizontal reference line on the wall.
- Transfer the centerline of the vehicle to the wall, and mark a vertical tape line across the horizontal line corresponding to the center of each headlamp.
- Block the light from one headlamp, and turn the vertical adjusters until the most intense part of the beam is below the horizontal reference line.
- The horizontal aim is adjusted by turning the horizontal screws until the most intense part of the beam falls to the right of the vertical centerline of the headlamp.
- Repeat the same procedure with the other headlamp.

Following the above procedure, the researcher adjusted the headlamp aim for both light trucks.

Test Setup

The researcher developed a test setup consisting of a measuring screen to aid the data collection process. This measuring screen was made of two plywood sheets bolted to a wooden frame. The bottom sheet measured 144×55 inches and was at a height of 37 inches above the surface of the ground. The top sheet measured 144×41 inches and was at a height of 106 inches from the surface of the ground. A gap of 12 inches existed between the two plywood sheets, where no measurements were required. This setup allowed for the direct measurement of illuminance values at the required points. The positions of the horizontal and vertical test points were determined based on the headlamp height, headlamp separation, and distance of the vehicle from the measuring screen. Figure IV.3 shows this screen constructed to aid the data collection process. The researcher determined the H/V points for different distances and different values of α (headlamp divergence angle) independently for each vehicle and marked them on the screen.

FIGURE IV.3 Field Setup

Test Procedure

The researcher arranged the test setup on the runway at Riverside Campus. The researcher conducted the aiming and illuminance measurements at night (completely dark atmosphere) to obtain accurate readings. The illuminance values measured in the field are affected by atmospheric transmissivity and can be an issue over long distances. The researcher did not consider the affects of transmissivity in this thesis.

For each vehicle all the required illuminance measurements were obtained in one session. The steps below were followed to measure the illuminance values:

- The researcher aimed the headlamps of the vehicle.
- After the aiming process, she attached a laser pointer to the vehicle to help constantly identify the longitudinal center line of the vehicle. The laser pointer aided in aligning the longitudinal axis of the vehicle along the center line of the pavement and perpendicular to the measuring screen.
- After attaching the laser pointer to the vehicle, the researcher drove each vehicle to the runway for the illuminance measurements.
- The researcher recorded the ambient illuminance reading before testing each vehicle. The ambient illuminance values always recorded to be 0 ft-c during the test period.
- She then positioned the measuring screen on the road with the right edge of the screen coinciding with the right edge line of the pavement.
- Next, she marked the centerline of the road on the measuring screen using retroreflective sign sheeting material. She also marked the calculated H/V measurement points on the screen using masking tape and a highlighter.
- She measured a distance of 125 ft from the measuring screen and aligned the vehicle at that point. She then aligned the centerline of the vehicle along the

centerline of the pavement by adjusting the vehicle's position so that the beam from the laser pointer was incident on the sign sheeting material attached to the measuring screen.

- With the aid of a voltmeter, the researcher then recorded the battery voltage of the running vehicle before starting the test.
- To reduce any light bouncing off the pavement, the researcher placed a cardboard screen between the vehicle and the measuring screen.
- She then placed the sensors of the illuminance meter on the measuring screen at the marked positions. Figure IV.4 shows the placement of the sensors on the measuring screen.
- The researcher recorded the illuminance values for each headlamp individually. She used an opaque cloth to cover the headlamp not being measured.
- The researcher repeated the above process with the vehicle placed at 250 ft and 500 ft from the measuring screen.
- She then recorded the battery voltage of the running vehicle after taking all the required measurements.
- The researcher repeated the entire process for each vehicle.

FIGURE IV.4 Placement of Illuminance Meter Sensors on Measuring Screen

DATA ANALYSIS

This section shows the determination of illuminance values at the required points, comparison of field illuminance values to the theoretical values, and comparison of the Taurus and the light truck field illuminance values.

Calculation of Illuminance Values

Curve 1: The researcher used a design speed of 60 mph and corresponding SSD of 570 ft for Curve 1. An ‘A’ value of 6 percent and an ‘L’ value of 816 ft for the S<L condition was used. The vehicle was located at the start of the curve. For $\alpha = 1.0$ degree:

- The researcher converted the illuminance (E in ft-c) values (average of three readings) measured at 125 ft to luminous intensity (I in cd) values using Equation IV.1:

$$I = E * \left(\frac{S}{\cos(\alpha)} \right)^2 \qquad \text{(IV.1)}$$

- The same procedure was followed to calculate the luminous intensity values from the illuminance readings taken at 250 ft and 500 ft.
- The researcher determined the average of the luminous intensity values.
- From these luminous intensity values, she calculated the illuminance values at 570 ft using Equation IV.2:

$$E = \frac{I * 10.764}{\left(\frac{S}{\cos(\alpha)} \right)^2} \qquad \text{(IV.2)}$$

- The researcher calculated the illuminance values independently for each headlamp and then added them together to obtain the total illuminance values at each point.

She repeated the same process for α = 0.5 degree and for each of the four vehicles.

Curve 2: The researcher used a design speed of 65 mph and a corresponding SSD of 645 ft for Curve 2. An 'A' value of 6 percent and an 'L' value of 942 ft for the S<L condition was used. The vehicle was located at the start of the curve.

Curve 3: The researcher used a design speed of 70 mph and a corresponding SSD of 730 ft for Curve 3. An 'A' value of 4 percent and an 'L' of 724 ft for the S>L condition was used. The vehicle was located at the start of the curve.

Following the procedure described for calculating the illuminance values in Curve 1, the researcher calculated the illuminance values for Curves 2 and 3. Appendix A shows the different steps involved in calculating the illuminance values.

Comparison of Field and Theoretical Illuminance Values

The researcher compared the illuminance values calculated from the field to the illuminance values calculated using the theoretical luminous intensity data. The test voltage at which the theoretical luminous intensity values are calculated is different from the operating voltage of the vehicles. To account for this difference, the theoretical illuminance values required adjustment. The researcher used Equation IV.3 to adjust the theoretical illuminance values (*38*).

$$LI_{vc} = LI_{tv} * (\frac{V_2}{V_1})^{3.4} \qquad \text{(IV.3)}$$

Where:

LI_{vc} = Voltage-corrected luminous intensity

LI_{tv} = Luminous intensity at test voltage

V_1 = Test voltage

V_2 = Operating voltage

The researcher used a value of 12.8 v as the test voltage (V_1). The vehicles' average operating voltages (V_2) are shown in Table IV.2.

TABLE IV.2 Operating Voltage for Test Vehicles

	Ford Taurus		Chevrolet 2500 Light Truck	
	Car 1	Car 2	Light Truck 1	Light Truck 2
Start Voltage (v)	13.9	13.98	14.00	14.00
End Voltage (v)	13.4	13.48	13.80	13.78
Average (v)	13.65	13.73	13.90	13.89

The researcher applied an adjustment factor directly to the theoretical illuminance values to account for the operating voltage of each car, and the average theoretical values for each type were determined. Tables IV.3, IV.4, and IV.5 show the comparison of field and theoretical illuminance values for the Taurus cars.

TABLE IV.3 Comparison of Field and Theoretical Illuminance Values for Taurus – Curve 1

Distance to the left of right edge line, d (ft)	Curve 1, α = 1.0°			Curve 1, α = 0.5°		
	Field E (lx)	Theoretical E (lx)	% Change	Field E (lx)	Theoretical E (lx)	% Change
12	0.08	0.052	32.08	0.19	0.091	51.73
10	0.08	0.054	34.22	0.21	0.097	53.40
8	0.08	0.056	31.42	0.21	0.102	51.72
6	0.09	0.057	34.24	0.22	0.106	52.00
4	0.09	0.059	36.74	0.23	0.108	52.17
2	0.10	0.060	38.36	0.25	0.110	55.05
0	0.09	0.061	33.01	0.24	0.112	52.34
Average	0.09	0.057	34.30	0.22	0.104	52.63

TABLE IV.4 Comparison of Field and Theoretical Illuminance Values for Taurus – Curve 2

Distance to the left of right edge line, d (ft)	Curve 2, α = 1.0°			Curve 2, α = 0.5°		
	Field E (lx)	Theoretical E (lx)	% Change	Field E (lx)	Theoretical E (lx)	% Change
12	0.05	0.041	18.89	0.15	0.073	52.55
10	0.05	0.042	21.72	0.17	0.077	53.94
8	0.05	0.044	18.52	0.17	0.08	51.56
6	0.06	0.045	20.57	0.17	0.083	51.52
4	0.06	0.046	24.27	0.17	0.084	51.46
2	0.07	0.047	29.66	0.19	0.086	54.89
0	0.06	0.047	24.67	0.18	0.087	51.05
Average	0.06	0.045	22.61	0.17	0.081	52.42

TABLE IV.5 Comparison of Field and Theoretical Illuminance Values for Taurus – Curve 3

Distance to the left of right edge line, d (ft)	Curve 3, α = 1.0°			Curve 3, α = 0.5°		
	Field E (lx)	Theoretical E (lx)	% Change	Field E (lx)	Theoretical E (lx)	% Change
12	0.05	0.033	34.97	0.12	0.058	52.34
10	0.05	0.033	36.23	0.13	0.061	53.98
8	0.05	0.034	33.77	0.13	0.063	52.03
6	0.05	0.035	33.93	0.14	0.064	52.50
4	0.06	0.036	36.69	0.14	0.066	52.28
2	0.06	0.036	37.37	0.15	0.067	54.97
0	0.06	0.037	34.16	0.15	0.068	53.51
Average	0.05	0.035	35.30	0.14	0.064	53.09

Tables IV.5, IV.6, and IV.7 show the comparison of field illuminance values of the light truck to the theoretical illuminance values of a 92×150 sealed beam headlamp (the closest match to the Light Truck headlamps that the researcher could obtain).

TABLE IV.6 Comparison of Field and Theoretical Illuminance Values for Light Truck – Curve 1

Distance to the left of right edge line, d (ft)	Curve 1, α = 1.0°			Curve 1, α = 0.5°		
	Field E (lx)	Theoretical E (lx)	% Change	Field E (lx)	Theoretical E (lx)	% Change
12	0.15	0.071	53.01	0.27	0.158	41.34
10	0.15	0.074	50.84	0.29	0.171	40.83
8	0.16	0.077	50.36	0.30	0.184	38.09
6	0.16	0.081	50.25	0.32	0.198	37.66
4	0.16	0.086	47.38	0.33	0.215	34.23
2	0.17	0.091	46.56	0.45	0.234	48.35
0	0.17	0.098	41.47	0.36	0.254	29.67
Average	0.16	0.083	48.55	0.33	0.202	38.60

TABLE IV.7 Comparison of Field and Theoretical Illuminance Values for Light Truck – Curve 2

Distance to the left of right edge line, d (ft)	Curve 2, α = 1.0°			Curve 2, α = 0.5°		
	Field E (lx)	Theoretical E (lx)	% Change	Field E (lx)	Theoretical E (lx)	% Change
12	0.09	0.056	37.43	0.21	0.127	40.56
10	0.10	0.058	38.29	0.23	0.136	40.12
8	0.10	0.061	38.07	0.23	0.145	37.87
6	0.10	0.063	38.01	0.25	0.155	37.14
4	0.10	0.066	35.85	0.25	0.166	34.70
2	0.11	0.070	35.01	0.27	0.179	34.51
0	0.11	0.075	30.39	0.28	0.192	31.31
Average	0.10	0.064	36.15	0.25	0.157	36.60

TABLE IV.8 Comparison of Field and Theoretical Illuminance Values for Light Truck – Curve 3

Distance to the left of right edge line, d (ft)	Curve 3, α = 1.0°			Curve 3, α = 0.5°		
	Field E (lx)	Theoretical E (lx)	% Change	Field E (lx)	Theoretical E (lx)	% Change
12	0.09	0.045	50.26	0.17	0.101	40.74
10	0.09	0.046	50.67	0.18	0.108	39.51
8	0.10	0.047	50.82	0.18	0.114	38.00
6	0.10	0.049	51.20	0.20	0.121	38.15
4	0.10	0.052	49.89	0.20	0.128	36.69
2	0.11	0.054	48.83	0.21	0.137	35.89
0	0.10	0.057	45.28	0.22	0.146	33.25
Average	0.10	0.050	49.56	0.19	0.122	37.46

By observing the percent change values between the field and theoretical illuminance values in the above tables, it can be seen that they differ considerably. The exact same headlamps used on the vehicles were not tested to obtain the theoretical data, but data from similar headlamps were used. This could account for some part of the variation in the data.

Comparison of Taurus and Light Truck Field Illuminance Values

To examine the change in beam pattern in the Taurus headlamps compared to headlamps of the light truck, the researcher calculated the percentage change in the amount of light produced by these headlamps for H_v angles of 1.0 degree and 0.5 degree. Table IV.9, shows the illuminance comparison for Curve 1. The graphical representation of the comparison is shown in Figure IV.5.

TABLE IV.9 Difference in Illuminance Values for the Headlamps of Taurus and Light Truck for Curve 1

Distance to the left of right edge line, d (ft)	Illuminance (lx)			% Change	
	Taurus 1°	Light Truck 1°	Taurus 0.5°	Taurus 1°-Light Truck 1°	Taurus 0.5°-Light Truck 1°
12	0.08	0.15	0.19	-49.47	24.34
10	0.08	0.15	0.21	-45.66	37.85
8	0.08	0.16	0.21	-47.89	35.35
6	0.09	0.16	0.22	-46.69	34.98
4	0.09	0.16	0.23	-42.98	38.59
2	0.10	0.17	0.24	-43.30	43.10
0	0.09	0.17	0.24	-46.07	39.98
Average	0.09	0.16	0.22	-46.01	36.31

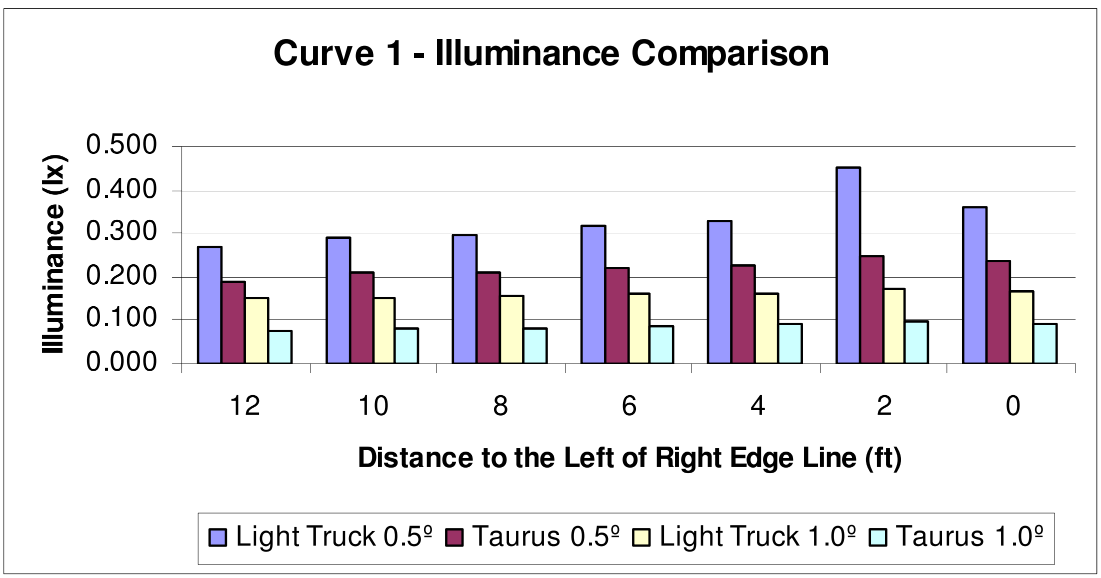


FIGURE IV.5 Comparison of Illuminance Values for the Headlamps of Taurus and Light Truck for Curve 1

Table IV.10, shows the illuminance comparison for Curve 2. The graphical representation of the comparison is shown in Figure IV.6.

TABLE IV.10 Difference in Illuminance Values for the Headlamps of Taurus and Light Truck for Curve 2

Distance to the left of right edge line, d (ft)	Illuminance (lx)			% Change	
	Taurus 1º	Light Truck 1º	Taurus 0.5º	Taurus 1°-Light Truck 1°	Taurus 0.5°-Light Truck 1°
12	0.05	0.09	0.15	-43.66	69.71
10	0.05	0.09	0.17	-42.86	76.36
8	0.05	0.10	0.17	-45.26	69.03
6	0.06	0.10	0.17	-44.85	66.76
4	0.06	0.10	0.17	-41.45	67.94
2	0.07	0.11	0.19	-38.80	75.67
0	0.06	0.11	0.18	-41.43	66.11
Average	0.06	0.10	0.17	-42.62	70.23

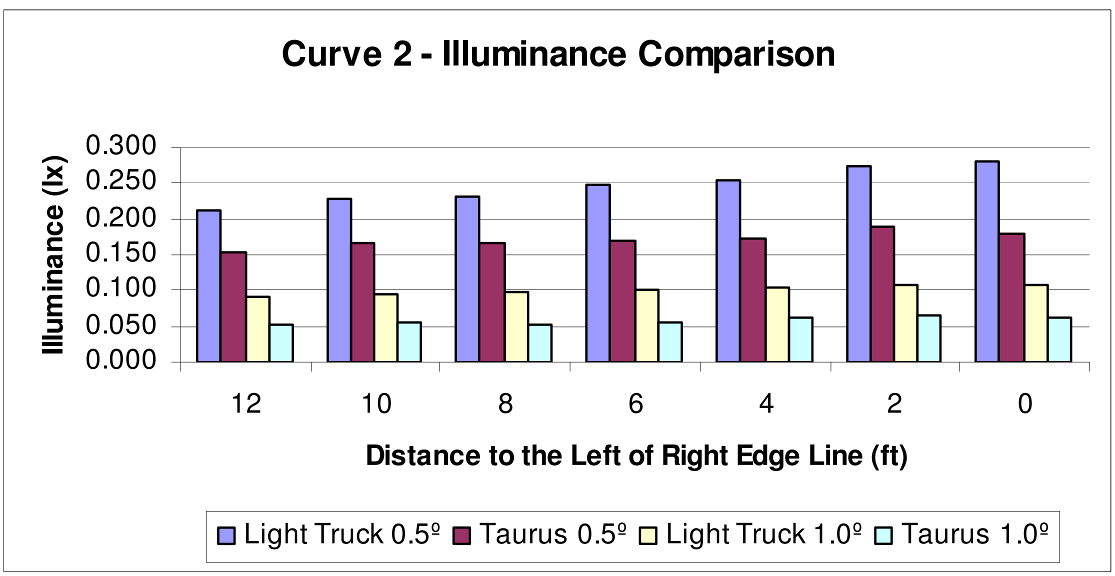


FIGURE IV.6 Comparison of Illuminance Values for the Headlamps of Taurus and Light Truck for Curve 2

Table IV.11, shows the illuminance comparison for Curve 3. The graphical representation of the comparison is shown in Figure IV.7.

TABLE IV.11 Difference in Illuminance Values for the Headlamps of Taurus and Light Truck for Curve 3

Distance to the left of right edge line, d (ft)	Illuminance (lx)			% Change	
	Taurus 1.0º	Light Truck 1.0º	Taurus 0.5º	Taurus 1.0°- Light Truck 1.0°	Taurus 0.5°- Light Truck 1.0°
12	0.05	0.09	0.12	-44.11	35.75
10	0.05	0.09	0.13	-43.79	41.74
8	0.05	0.10	0.13	-46.51	36.01
6	0.05	0.10	0.14	-47.67	34.34
4	0.06	0.10	0.14	-45.40	33.62
2	0.06	0.11	0.15	-45.17	40.34
0	0.06	0.10	0.15	-46.28	39.69
Average	0.05	0.10	0.14	-45.56	37.36

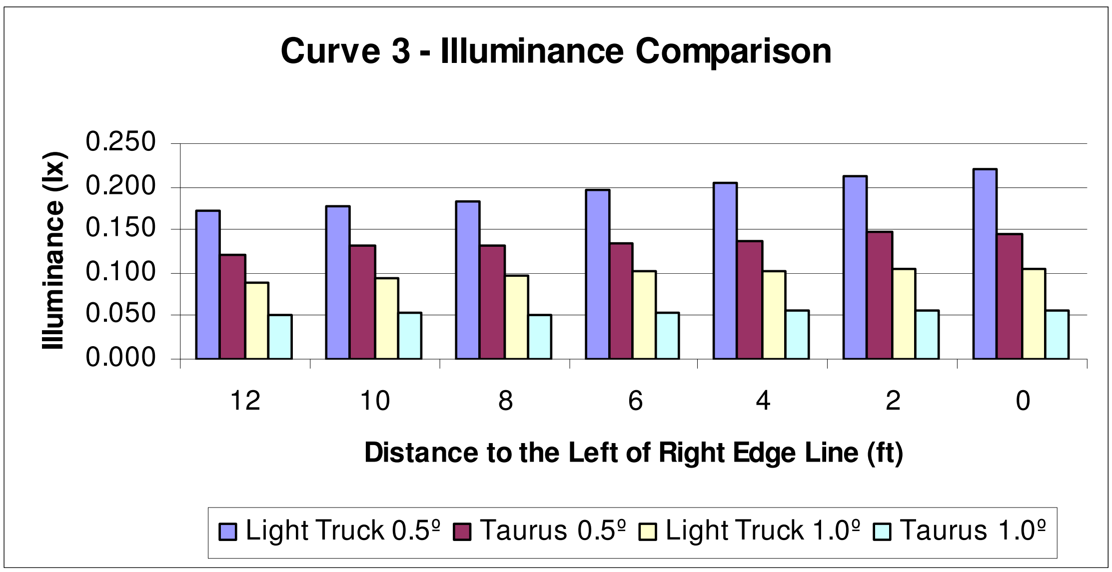


FIGURE IV.7 Comparison of Illuminance Values for the Headlamps of Taurus and Light Truck for Curve 3

These comparison tables show that the illuminance values differ significantly for the Taurus and the light truck. Illuminance values for the light truck are higher compared to the illuminance from the Taurus at H_v of 1.0 degree. When the illuminance values of the Taurus at H_v = 0.5 degree are compared to the illuminance values of the light truck at H_v = 1.0 degree, it is observed that the illuminance values from the Taurus are greater. This comparison shows that a H_v angle between 0.5 degree and 1.0 degree is required for the Taurus to have illuminance values comparable to those of the light truck at 1.0 degree. The analysis in Chapter III showed that a H_v = 0.85 degree is recommend for use with modern headlamps. The results from this chapter, stating the use of H_v between 0.5 and 1 degree support this statement. The illuminance from modern headlamps is less when compared to the illuminance from sealed beam headlamps at the SSD for each of the curves examined. The difference in illuminance values for the Taurus (sporting modern headlamps) and the light truck (sporting sealed beam headlamps) for H_v = 1.0 degree for the curves used in the analysis are listed below. The average difference in illuminance between the vehicles was calculated across the width of the road. The change in illuminance for,

Curve 1 : -46 %

Curve 2 : -42 %

Curve 3 : -46 %

CHAPTER V

DEGRADATION OF HEADLAMP LENSES STUDY

Degraded headlamp lenses scatter the light coming out of a headlamp. Degradation of lenses could have different impacts on the amount of light falling on the roadway. This chapter details the attempt to examine the degradation of headlamp lenses and its impact on the amount of light provided on a roadway.

TEST PROCEDURE AND RESULTS

The objective of this part of the study is to measure the illuminance at specific points using degraded and new headlamp lenses. The difference in these values will give an idea of the impact degraded lenses have on the illuminance at different points. This portion of the study was conducted with a basic approach to identify whether degraded headlamps have a significant impact on the illuminance produced.

Table V.1 gives information on the headlamp lenses used by the researcher for the study. Some of the lenses were undegraded, and others had different degrees of degradation. The relatively clear lenses were considered as undegraded, and the illuminance values were compared to those from the degraded lenses. All the headlamps had hard plastic lenses. The degradation depends on the amount of exposure each of these lenses had; the researcher did not have this information. The level of degradation did not depend on the model year.

TABLE V.1 Description of Lenses

	Chevrolet Corsica	GMC Sierra	
Model Year	1996	1997	1999
Undegraded Lens	1	1	-
Degraded Lens	1	-	1

For this task, the researcher arranged a test setup consisting of a laser pointer, headlamp, and illuminance meter, as shown in Figures V.1 and V.2. After removing the headlamp bulb, the researcher used a tripod to hold the laser pointer in its place. She then attached the sensors of the illuminance meter in front of the headlamp. The laser pointer and the sensors were spaced 3 ft apart. The illuminance from a laser pointer is very small when compared to a headlamp bulb. A distance of 3 ft was ideal to obtain readings at the required points. The laser pointer was positioned in such a manner that its beam passed through the center of the headlamp lens. The reading of sensor 'M' represents the illuminance of the beam at this position. The reading of this sensor corresponds to the reading of a 0 degree beam coming from the headlamp. The researcher measured illuminance values at four different points for eight headlamps--four with new and four with degraded lenses. Figure V.2 shows the position of the sensors of the illuminance meter; the left sensor is referred to by the letter 'L', middle sensor by the letter 'M', right sensor by the letter 'R,' and top sensor by the letter 'T.' The 'T' sensor is positioned to measure the illuminance of the 1.0 degree upward beam being diverged from the headlamp. The 'T' sensor was placed approximately 0.6 inches above the center of the 'M' sensor. The 'L' and 'R' sensors were placed next to the 'M' sensor. These test points would give an idea of the change in illuminance at different points on a headlamp due to degraded headlamp lens. The researcher used a Minolta T2 illuminance meter for illuminance measurements at the L, M, R, and T points.

FIGURE V.1 Test Setup for Headlamp Degradation Test

FIGURE V.2 Closer Views of the Illuminance Meter Sensors and Laser Pointer Fixed on a Tripod

To account for any variability in the observations, the researcher took five measurements at each point for each lens and averaged the values. The measurements at each point are presented in Appendix B. Table V.2 and V.3 show the average illuminance values measured at each of these points for new and degraded lenses. The percentage change column indicates the change (decrease) in illuminance values at the specified points.

TABLE V.2 Comparison of Illuminance Values (ft-c) for Chevrolet Corsica Headlamp Lenses

Position of Sensor	Undegraded Lens	Degraded Lens	% Change
L	0.110	0.064	-41.82
M	0.145	0.071	-51.03
T	0.087	0.065	-25.29
R	0.097	0.060	-38.14

TABLE V.3 Comparison of Illuminance Values (ft-c) for GMC Sierra Headlamp Lenses

Position of Sensor	Undegraded Lens	Degraded Lens	% Change
L	0.154	0.015	-90.26
M	0.162	0.025	-84.57
T	0.078	0.025	-67.95
R	0.065	0.018	-72.31

An examination of the illuminance values shows that degradation of lenses has a significant effect on the light emitted at different points. From this preliminary study it appears that the change in illuminance values is considerably large. This change indicates that the degradation in headlamp lenses would result in reduced amount of light reaching the road. The focus of this research is the amount of light reaching the road on sag curves. The illuminance values recorded at the 'T' sensor are indicative of the amount of light reaching the road on sag curves. An observation of these readings at the 'T' sensor show that degraded lenses will reduce the amount of light reaching the road on sag curves significantly. However, the results of this preliminary study were based on a small sample size using a simple test setup. Based on these results, it appears reasonable to conduct a detailed study examining lenses with different degrees of degradation.

CHAPTER VI

SUMMARY 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. 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. The objective of this research was to examine the impact of headlamp performance on the illuminance provided on sag curves; and based on the results to determine whether any changes are required in the design criteria.

The researcher calculated the theoretical illuminance values from different headlamps on different sag curves using a spreadsheet developed for this purpose. She then conducted a field study to validate the theoretical calculations. The field study simulated the conditions similar to the sag curves used in the theoretical analysis. Based on the comparison of illuminance values, she determined an upward headlamp divergence angle to be used with modern headlamps. As a part of this thesis, the researcher also conducted a degradation of headlamp lenses study to develop an understanding of its impact on the illuminance provided on a sag curve. Assess

FINDINGS

The illuminance produced by modern headlamps above the horizontal plane is significantly less than the illuminance produced by sealed beam headlamps that were used in developing sag curve design formulas.

The theoretical analysis showed that the illuminance produced at the Stopping Sight Distance (SSD) on sag curves by the 2004 model composite headlamp is about 26 percent less than the illuminance produced by the 1985-1990 model composite headlamp. Further analysis showed that changing the upward headlamp divergence angle (α) from 1 degree to 0.85 degrees in the design formula appears appropriate when using modern headlamps (for a sample of 2004 headlamps). Changing α from 1 degree to 0.85 degrees will increase the length of sag curves.

The field study supported the findings of the theoretical analysis. From the field study, it was observed that an α less than 1.0 degree and greater than 0.5 degrees appears appropriate when using modern headlamps.

Modern headlamps provide less illuminance when compared to sealed beam headlamps at a given distance. This results in less available headlight sight distance (S) when using modern headlamps. For example, on a curve of length of 1086 ft, A: 6 percent, and SSD<L, use of modern headlamps would reduce S by 11 percent. Figure VI.1 illustrates the change in S when using modern headlamps. S at α 0.85 degrees shows the headlight sight distance available for modern headlamps. This headlight sight distance is less than the SSD required for the given design speed. In order to provide a headlight sight distance equal to the SSD, the sag curve length should be increased. This

is can be done by using equations VI.1 and VI.2. Using these equations resulted in an increase in curve length by 14.0, 14.5, and 14.8 percent for Curves 1, 2, and 3, used in the analysis, respectively.

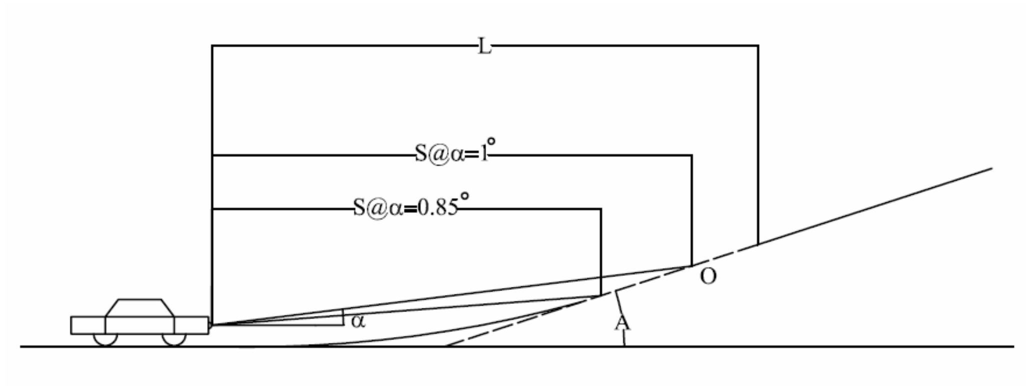


FIGURE VI.1 Stopping Sight Distance for Different Values of α

A part of this research focused on examining the impact of degraded headlamp lenses on the illuminance provided on sag curves. The researcher observed that degraded headlamp lenses have an adverse effect on the light reaching the road on sag curves.

LIMITATIONS

The findings of this research have the following limitations:

- The researcher could not obtain information providing the original basis for the use of an α of 1 degree in the design formula. Consequently the illuminance level that served as the basis for developing the sag curve design formula was not available. Due to this lack of information, the researcher used the illuminance levels provided by CARTS composite headlamp data comprising of 1985-1990 model year headlamps as a basis for comparing the illuminance from modern headlamps.

- The findings of the theoretical and field study in this research are based on a small headlamp data sample and do not represent the different types of headlamps used on the roadway.
- The degradation study was performed on a very small sample of headlamps. The findings do not represent lenses with different degrees of degradation. Different factors like voltage and misaim were not accounted for.

RECOMMENDATIONS

The findings in the theoretical analysis show that using an α of 0.85 degrees in the sag curve design formula for modern headlamps (2004 model) will give illuminance values close to the 1985-1990 model headlamps. Change in α from 1 degree to 0.85 degrees will increase the length of sag curves. This modification would potentially provide safer driving conditions at night on sag curves. The changed design formulas are shown in Equations VI.1 and VI.2.

$$L = \frac{AS^2}{200[2.0 + S\tan 0.85°]} = \frac{AS^2}{400 + 2.97S} \qquad \text{(VI.1)}$$

$$L = 2S - \frac{200[h + S\tan 0.85°]}{A} = 2S - \frac{400 + 2.97S}{A} \qquad \text{(VI.2)}$$

The findings from the field analysis support the findings of the theoretical analysis. Based on the field study it appears that using an α less than 1 degree and greater than 0.5 degrees is appropriate for modern headlamps. However, these recommendations are based on the minimal data available to the researcher and should not be implemented until further research is conducted.

The findings from the degradation study indicate that it maybe appropriate to consider the impact of headlamp degradation on nighttime visibility, including sag curve design. A detailed study is required to determine the impact of various degrees of degradation of lenses on roadway illuminance.

FUTURE RESEARCH

The researcher recommends the following areas be considered in future research:

- The recommended change in α was based on a limited set of headlamp data. Headlamp data from a wide range of headlamps should be analyzed to have a better representation of the vehicle fleet. Further research is required to determine the most appropriate value of α to be used in the design formula when using modern headlamps.
- The current sag curve design formula use a headlamp mounting height of 2.0 ft. However, a significant portion of the present vehicle fleet has higher headlamp mounting height. Use of smaller heights in the formula when the actual mounting height is larger results in longer sag curves (more conservative design). The impact of changing headlamp beam pattern could be countered by an increase the headlamp mounting height. Further research

is required to observe the trend of headlamp mounting height in combination with the changed beam pattern.

- The researcher did not consider many factors like bulb output and lens degradation in the analysis. These factors should also be considered to have a better representation of the field conditions.
- The researcher did not consider the requirements of older drivers in this study. It might be appropriate to modify the design formula based on the illuminance requirements of older drivers.
- The researcher did not examine the safety issues related to the length of a sag curve. This is an important factor to be considered in future research.
- The researcher would also recommend considering the impact of increased sag curve length on construction costs.

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APPENDIX A

Table A.1 lists the physical characteristics and battery voltage of the vehicles used in the field study.

TABLE A.1 Vehicle Characteristics

		Headlamp Height (in)	**Headlamp Separation (in)**	**Start Voltage (Volts)**	**End Voltage (Volts)**
Ford Taurus	Car 1	26.5	46.0	13.90	13.40
	Car 2	26.5	46.0	13.98	13.48
Chevy 2500 Light Truck	Car 1 - 95	36.0	57.0	14.00	13.80
	Car 2 - 97	36.0	57.0	14.00	13.78

The researcher used H_h angles in the determining the illuminance values from the theoretical data. Table A.2 lists the Taurus horizontal headlamp angles for curve 1. Equation A.1 shows the calculation of H_h angle for the left headlamp of Taurus Car 1on Curve 1.

$$H_h = \tan^{-1}\left(\frac{(\frac{w}{2} - d \pm \frac{l}{2})}{S}\right) \tag{A.1}$$

Model Calculation:

w = 12 ft, d = 6 ft, l = 3.833, S = 570 ft

$$= \tan^{-1}\left(\frac{\frac{12}{2} - 6 + \frac{3.833}{2}}{570}\right) = 0.193°$$

TABLE A.2 Horizontal Headlamp Angles for Taurus - Curve 1

Distance to the left of right edge line, d (ft)	Horizontal angle, Hh(α°)	
	Left headlight	Right headlight
0	0.796	0.410
2	0.595	0.210
4	0.394	0.009
6	0.193	-0.193
8	-0.009	-0.394
10	-0.210	-0.595
12	-0.410	-0.796

The field illuminance data for Curve 1, H_v: 1.0 degree collected with the Taurus Car 1 at a distance of 125 ft are listed in Table A.3. The researcher took three readings at each observation point and averaged them. Readings were recorded separately for the left and right headlamps. Using the illuminance (E in ft-c) values measured at 125 ft, the researcher calculated the corresponding luminous intensity (I in cd) values using Equation A.2,

$$I = E * \left(\frac{S}{\cos(\alpha)}\right)^2 \qquad \text{(A.2)}$$

Model Calculation:

Left Headlamp:

S = 125 ft; α = 1.0°

For an observation point at d = 89.94 in from the right edge line, from Table A.3,

Avg E = 0.58 ft-c,

$$I = 0.058 * \left(\frac{125}{\cos(1.0)}\right)^2 = 906.526 \text{ cd}$$

TABLE A.3 Illuminance Values for Curve 1 at S = 125 ft and H_v: 1.0 degree - Taurus Car 1

Left Headlamp						
Distance to the left of right edge line, d (in)	**E (ft-c)**			**Avg**	**E (lx)**	**I (cd)**
105.73	0.044	0.042	0.048	0.04467	0.481	698.13
100.47	0.056	0.059	0.051	0.05533	0.596	864.85
95.2	0.051	0.055	0.054	0.05333	0.574	833.59
89.94	0.057	0.060	0.057	0.05800	0.624	906.53
84.68	0.054	0.059	0.060	0.05767	0.621	901.32
79.41	0.063	0.068	0.071	0.06733	0.725	1052.40
74.15	0.058	0.064	0.062	0.06133	0.660	958.63
Right Headlamp						
69.85	0.060	0.074	0.060	0.06467	0.696	1010.73
64.59	0.065	0.056	0.063	0.06133	0.660	958.63
59.32	0.066	0.068	0.072	0.06867	0.739	1073.24
54.06	0.076	0.104	0.111	0.09700	1.044	1516.09
48.8	0.085	0.135	0.142	0.12067	1.299	1885.99
43.53	0.110	0.184	0.197	0.16367	1.762	2558.07
38.27	0.115	0.115	0.120	0.11667	1.256	1823.47

The field illuminance data collected at 250 ft and 500 ft using Taurus Car 1 are listed in Table A.4 and A.5 respectively. The corresponding luminous intensities are also listed.

TABLE A.4 Illuminance Values for Curve 1 at S = 250 ft and H_v: 1.0 degree - Taurus Car 1

Left Headlamp						
Distance to the left of right edge line, d (in)	**E (ft-c)**			**Avg**	**E (lx)**	**I (cd)**
116.48	0.013	0.024	0.022	0.0196667	0.212	1229.54
105.95	0.014	0.024	0.025	0.0210000	0.226	1312.90
95.43	0.012	0.025	0.026	0.0210000	0.226	1312.90
84.9	0.014	0.024	0.022	0.0200000	0.215	1250.38
74.37	0.012	0.024	0.018	0.0180000	0.194	1125.34
63.85	0.015	0.024	0.016	0.0183333	0.197	1146.18
53.32	0.013	0.025	0.018	0.0186667	0.201	1167.02
Right Headlamp						
90.68	0.016	0.013	0.017	0.0153333	0.165	958.63
80.15	0.019	0.014	0.017	0.0166667	0.179	1041.98
69.63	0.018	0.014	0.018	0.0166667	0.179	1041.98
59.1	0.020	0.014	0.023	0.019	0.205	1187.86
48.57	0.023	0.013	0.028	0.0213333	0.23	1333.74
38.05	0.025	0.014	0.020	0.0196667	0.212	1229.54
27.52	0.028	0.016	0.022	0.022	0.237	1375.42

TABLE A.5 Illuminance Values for Curve 1 at S = 500 ft and H_v: 1.0 degree - Taurus Car 1

Left Headlamp						
Distance to the left of right edge line, d (in)	**E (ft-c)**			**Avg (ft-c)**	**E (lx)**	**I (cd)**
137.98	0.001	0.002	0.001	0.0013333	0.014	333.44
116.93	0.001	0.002	0.001	0.0013333	0.014	333.44
95.87	0.001	0.002	0.002	0.0016667	0.018	416.79
74.82	0.001	0.002	0.002	0.0016667	0.018	416.79
53.77	0.001	0.003	0.002	0.0020000	0.022	500.15
32.72	0.001	0.003	0.003	0.0023333	0.025	583.51
11.66	0.001	0.003	0.003	0.0023333	0.025	583.51
Right Headlamp						
132.34	0.009	0.007	0.008	0.0080000	0.086	2000.61
111.28	0.009	0.007	0.008	0.0080000	0.086	2000.61
90.23	0.009	0.007	0.008	0.0080000	0.086	2000.61
69.18	0.009	0.007	0.008	0.0080000	0.086	2000.61
48.13	0.009	0.007	0.008	0.0080000	0.086	2000.61
27.07	0.009	0.007	0.007	0.0076667	0.083	1917.25
6.02	0.009	0.007	0.007	0.0076667	0.083	1917.25

The researcher averaged the luminous intensity values calculated from measurements at 125 ft, 250 ft, and 500 ft-corresponding to Curve 1. Table A.6 lists the average luminous intensity values. Using these values, the researcher calculated the illuminance values at 570 ft using Equation A.3,

$$E = \frac{I * 10.764}{\left(\frac{S}{\cos(\alpha)}\right)^2} \qquad \text{(A.3)}$$

Model Calculation:

Left Headlamp:

S = 570 ft, α = 1.0°

I = 857.9 cd at d = 6 ft (from Table A.6)

$$E = \frac{857.9 * 10.764}{\left(\frac{570}{\cos(1.0)}\right)^2} = 0.028 \text{ lx}$$

TABLE A.6 Illuminance Values for Curve 1 and H_v: 1.0 degree - Taurus Car 1

Distance to the left of right edge line, d (ft)	Left Headlamp		Right Headlamp		Total E (lx)
	Avg I (cd)	E (lx)	Avg I (cd)	E (lx)	
12	753.702	0.025	1323.32	0.044	0.069
10	837.061	0.028	1333.74	0.044	0.072
8	854.427	0.028	1371.95	0.045	0.074
6	857.900	0.028	1568.19	0.052	0.080
4	842.270	0.028	1740.11	0.058	0.086
2	927.366	0.031	1901.62	0.063	0.094
0	903.053	0.030	1705.38	0.056	0.086

The same procedure was followed to determine the illuminance values using Taurus Car 2 on Curve 1. These values are tabulated in the following tables.

TABLE A.7 Illuminance Values for Curve 1 at S = 125 ft and H_v: 1.0 degree - Taurus Car 2

Left Headlamp						
Distance to the left of right edge line, d (in)	**E (ft-c)**			**Avg (ft-c)**	**E (lx)**	**I (cd)**
105.73	0.025	0.079	0.022	0.0420000	0.452	656.45
100.47	0.026	0.092	0.024	0.0473333	0.509	739.81
95.2	0.027	0.085	0.028	0.0466667	0.502	729.39
89.94	0.029	0.095	0.026	0.0500000	0.538	781.49
84.68	0.028	0.093	0.031	0.0506667	0.545	791.91
79.41	0.032	0.111	0.035	0.0593333	0.639	927.37
74.15	0.026	0.101	0.026	0.0510000	0.549	797.12
Right Headlamp						
69.85	0.092	0.097	0.093	0.0940000	1.012	1469.20
64.59	0.107	0.113	0.102	0.1073333	1.155	1677.59
59.32	0.100	0.106	0.111	0.1056667	1.137	1651.55
54.06	0.105	0.111	0.117	0.1110000	1.195	1734.90
48.8	0.105	0.113	0.120	0.1126667	1.213	1760.95
43.53	0.125	0.131	0.128	0.1280000	1.378	2000.61
38.27	0.115	0.122	0.123	0.1200000	1.292	1875.57

TABLE A.8 Illuminance Values for Curve 1 at S = 250 ft and H_v: 1.0 degree - Taurus Car 2

Left Headlamp						
Distance to the left of right edge line, d (in)	**E (ft-c)**			**Avg**	**E (lx)**	**I (cd)**
53.32	0.012	0.016	0.011	0.0130000	0.140	812.75
63.85	0.014	0.02	0.014	0.0160000	0.172	1000.31
74.37	0.013	0.019	0.017	0.0163333	0.176	1021.14
84.9	0.014	0.022	0.021	0.0190000	0.205	1187.86
95.43	0.016	0.020	0.025	0.0203333	0.219	1271.22
105.95	0.018	0.020	0.023	0.0203333	0.219	1271.22
116.48	0.016	0.019	0.019	0.0180000	0.194	1125.34
Right Headlamp						
90.68	0.025	0.023	0.022	0.0233333	0.251	1458.78
80.15	0.029	0.028	0.023	0.0266667	0.287	1667.17
69.63	0.026	0.025	0.027	0.0260000	0.28	1625.50
59.1	0.029	0.027	0.025	0.0270000	0.291	1688.01
48.57	0.028	0.028	0.025	0.0270000	0.291	1688.01
38.05	0.034	0.032	0.029	0.0316667	0.341	1979.77
27.52	0.032	0.030	0.028	0.0300000	0.323	1875.57

TABLE A.9 Illuminance Values for Curve 1 at S = 500 ft and H_v: 1.0 degree - Taurus Car 2

Left Headlamp						
Distance to the left of right edge line, d (in)	E (ft-c)			Avg (ft-c)	E (lx)	I (cd)
137.98	0.009	0.006	0.006	0.0070000	0.075	1750.53
116.93	0.009	0.006	0.006	0.0070000	0.075	1750.53
95.87	0.009	0.005	0.006	0.0066667	0.072	1667.17
74.82	0.009	0.004	0.006	0.0063333	0.068	1583.82
53.77	0.009	0.005	0.008	0.0073333	0.079	1833.89
32.72	0.009	0.003	0.006	0.0060000	0.065	1500.46
11.66	0.009	0.003	0.006	0.0060000	0.065	1500.46
Right Headlamp						
132.34	0.007	0.005	0.006	0.0060000	0.065	1500.46
111.28	0.007	0.005	0.006	0.0060000	0.065	1500.46
90.23	0.007	0.004	0.005	0.0053333	0.057	1333.74
69.18	0.008	0.005	0.005	0.0060000	0.065	1500.46
48.13	0.008	0.005	0.008	0.0070000	0.075	1750.53
27.07	0.008	0.003	0.006	0.0056667	0.061	1417.10
6.02	0.008	0.003	0.006	0.0056667	0.061	1417.10

TABLE A.10 Illuminance Values for Curve 1 and H_v: 1.0 degree – Taurus Car 2

Distance to the left of right edge line, d (ft)	Left Headlamp		Right Headlamp		Total E (lx)
	Avg I (cd)	E (lx)	Avg I (cd)	E (lx)	
12	1073.244	0.036	1476.144	0.049	0.084
10	1163.549	0.039	1615.075	0.053	0.092
8	1139.236	0.038	1536.926	0.051	0.089
6	1184.389	0.039	1641.125	0.054	0.094
4	1299.007	0.043	1733.167	0.057	0.100
2	1233.014	0.041	1799.159	0.060	0.100
0	1140.973	0.038	1722.747	0.057	0.095

Table A.11 shows the field and theoretical illuminance values for Curve 1, at H_v: 1.0 degree. The theoretical values are adjusted for field voltage using equation A.4. The theoretical values are adjusted separately for Taurus Car 1, and Car 2 separately and the average illuminance at each observation point is determined.

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

$$E_{vc} = E_{tv} * (\frac{V_2}{V_1})^{3.4}$$

Model Calculation:

V_1: 12.8 v, V_2: 13.65 v

From table A.11 at d = 6 ft, E_{tv} = 0.046 lx

$$E_{vc} = 0.046 * \left(\frac{13.65}{12.8}\right)^{3.4} = 0.057 \text{ lx}$$

TABLE A.11 Comparison of Field and Theoretical Illuminance Values for Taurus - Curve 1 and H_v: 1.0 degree

Distance to the left of right edge line, d (ft)	Field			Theoretical				% Change
	E-Car 1 (lx)	E-Car 2 (lx)	Average (lx)	E (lx)	Corrected E-Car 1 (lx)	Corrected E-Car 2 (lx)	Average (lx)	
12	0.069	0.084	0.077	0.041	0.052	0.053	0.052	32.08
10	0.072	0.092	0.082	0.043	0.054	0.055	0.054	34.06
8	0.074	0.089	0.081	0.044	0.055	0.056	0.056	31.42
6	0.080	0.094	0.087	0.046	0.057	0.058	0.057	34.10
4	0.086	0.100	0.093	0.047	0.058	0.059	0.059	36.74
2	0.094	0.100	0.097	0.048	0.059	0.061	0.060	38.23
0	0.086	0.095	0.091	0.048	0.060	0.061	0.061	33.01

Following the same procedure described to determine the illuminance values for Curve 1 at H_v: 1.0 degree, the illuminance values for different curves using different cars were determined. The following tables show the final illuminance values for each of these curves.

TABLE A.12 Horizontal Headlamp Angles for Taurus - Curve 2

Distance to the left of right edge line, d (ft)	Horizontal angle, Hh(α°)	
	Left headlight	Right headlight
0	0.703	0.363
2	0.525	0.185
4	0.348	0.007
6	0.170	-0.170
8	-0.007	-0.348
10	-0.185	-0.525
12	-0.363	-0.703

TABLE A.13 Comparison of Field and Theoretical Illuminance Values for Taurus - Curve 2 and H_v: 1.0 degree

Distance to the left of right edge line, d (ft)	Field			Theoretical				% Change
	E-Car 1 (lx)	E-Car 2 (lx)	Average (lx)	E (lx)	Corrected E-Car 1 (lx)	Corrected E-Car 2 (lx)	Average (lx)	
12	0.038	0.064	0.051	0.0327	0.041	0.042	0.041	19.14
10	0.040	0.069	0.054	0.0338	0.042	0.043	0.042	21.49
8	0.040	0.067	0.054	0.0347	0.043	0.044	0.044	18.52
6	0.044	0.069	0.056	0.0356	0.044	0.045	0.045	20.57
4	0.047	0.074	0.061	0.0364	0.045	0.046	0.046	24.47
2	0.053	0.079	0.066	0.0371	0.046	0.047	0.047	29.46
0	0.050	0.075	0.063	0.0376	0.047	0.048	0.047	24.67

TABLE A.14 Horizontal Headlamp Angles for Taurus - Curve 3

Distance to the left of right edge line, d (ft)	Horizontal angle, Hh(α°)	
	Left headlight	Right headlight
0	0.621	0.320
2	0.464	0.163
4	0.308	0.006
6	0.151	-0.151
8	-0.006	-0.308
10	-0.163	-0.464
12	-0.320	-0.621

TABLE A.15 Comparison of Field and Theoretical Illuminance Values for Taurus - Curve 3 and H_v: 1.0 degree

Distance to the left of right edge line, d (ft)	Field			Theoretical				% Change
	E-Car 1 (lx)	E-Car 2 (lx)	Average (lx)	E (lx)	Corrected E-Car 1 (lx)	Corrected E-Car 2 (lx)	Average (lx)	
12	0.044	0.056	0.050	0.026	0.032	0.033	0.033	34.97
10	0.044	0.06	0.052	0.027	0.033	0.034	0.033	36.23
8	0.046	0.057	0.052	0.027	0.034	0.035	0.034	33.77
6	0.047	0.059	0.053	0.028	0.035	0.035	0.035	33.93
4	0.050	0.062	0.056	0.028	0.035	0.036	0.036	36.46
2	0.052	0.063	0.058	0.029	0.036	0.037	0.036	37.37
0	0.051	0.061	0.056	0.029	0.036	0.037	0.037	34.16

TABLE A.16 Horizontal Headlamp Angles for Light Truck - Curve 1

Distance to the left of right edge line, d (ft)	Horizontal angle, Hh(α°)	
	Left headlight	Right headlight
0	0.842	0.364
2	0.641	0.163
4	0.440	-0.038
6	0.239	-0.239
8	0.038	-0.440
10	-0.163	-0.641
12	-0.364	-0.842

TABLE A.17 Comparison of Field and Theoretical Illuminance Values for Light Truck - Curve 1 and H_v: 1.0 degree

Distance to the left of right edge line, d (ft)	Field			Theoretical				% Change
	E-Car 1 (lx)	E-Car 2 (lx)	Average (lx)	E (lx)	Corrected E-Car 1 (lx)	Corrected E-Car 2 (lx)	Average (lx)	
12	0.132	0.172	0.152	0.054	0.071	0.071	0.071	53.01
10	0.139	0.162	0.151	0.056	0.074	0.074	0.074	50.84
8	0.146	0.165	0.156	0.059	0.077	0.077	0.077	50.36
6	0.148	0.178	0.163	0.061	0.081	0.081	0.081	50.25
4	0.149	0.177	0.163	0.065	0.086	0.086	0.086	47.38
2	0.157	0.185	0.171	0.069	0.092	0.091	0.091	46.56
0	0.157	0.179	0.168	0.074	0.098	0.098	0.098	41.47

TABLE A.18 Horizontal Headlamp Angles for Light Truck - Curve 2

Distance to the left of right edge line, d (ft)	Horizontal angle, Hh(α°)	
	Left headlight	Right headlight
0	0.744	0.322
2	0.566	0.144
4	0.388	-0.033
6	0.211	-0.211
8	0.033	-0.388
10	-0.144	-0.566
12	-0.322	-0.744

TABLE A.19 Comparison of Field and Theoretical Illuminance Values for Light Truck - Curve 2 and H_v: 1.0 degree

Distance to the left of right edge line, d (ft)	Field			Theoretical				% Change
	E-Car 1 (lx)	E-Car 2 (lx)	Average (lx)	E (lx)	Corrected E-Car 1 (lx)	Corrected E-Car 2 (lx)	Average (lx)	
12	0.085	0.096	0.090	0.043	0.057	0.056	0.056	37.43
10	0.089	0.100	0.095	0.044	0.059	0.058	0.058	38.29
8	0.089	0.107	0.098	0.046	0.061	0.060	0.061	38.07
6	0.095	0.110	0.102	0.048	0.063	0.063	0.063	38.01
4	0.096	0.111	0.103	0.050	0.066	0.066	0.066	35.85
2	0.101	0.115	0.108	0.053	0.070	0.070	0.070	35.01
0	0.100	0.114	0.107	0.056	0.075	0.074	0.075	30.39

TABLE A.20 Horizontal Headlamp Angles for Light Truck - Curve 3

Distance to the left of right edge line, d (ft)	Horizontal angle, Hh(α°)	
	Left headlight	Right headlight
0	0.657	0.285
2	0.500	0.128
4	0.343	-0.029
6	0.186	-0.186
8	0.029	-0.343
10	-0.128	-0.500
12	-0.285	-0.657

TABLE A.21 Light Truck Field and Theoretical Illuminance Values for Curve 3 and H_v: 1.0 degree

Distance to the left of right edge line, d (ft)	Field			Theoretical				% Change
	E-Car 1 (lx)	E-Car 2 (lx)	Average (lx)	E (lx)	Corrected E-Car 1 (lx)	Corrected E-Car 2 (lx)	Average (lx)	
12	0.084	0.095	0.090	0.034	0.045	0.044	0.045	50.26
10	0.088	0.099	0.093	0.035	0.046	0.046	0.046	50.67
8	0.091	0.102	0.097	0.036	0.048	0.047	0.047	50.82
6	0.093	0.109	0.101	0.037	0.049	0.049	0.049	51.20
4	0.097	0.109	0.103	0.039	0.052	0.051	0.052	49.89
2	0.096	0.115	0.105	0.041	0.054	0.054	0.054	48.83
0	0.095	0.113	0.104	0.043	0.057	0.057	0.057	45.28

APPENDIX B

Degradation Study Data

The following tables show the illuminance values measured using an illuminance meter and its sensors at the required positions.

TABLE B.1 Illuminance Values for New Lenses of a Chevrolet Corsica - 96 Headlamp

Position of Heads	Illuminance Readings (ft-c)					
	1	2	3	4	5	Mean
L	0.115	0.105	0.110	0.105	0.116	0.110
M	0.141	0.148	0.143	0.148	0.145	0.145
T	0.090	0.082	0.085	0.086	0.091	0.087
R	0.100	0.090	0.089	0.084	0.12	0.097

TABLE B.2 Illuminance Values for Degraded Lenses of a Chevrolet Corsica - 96 Headlamp

Position of Heads	Illuminance Readings (ft-c)					
	1	2	3	4	5	Mean
L	0.060	0.066	0.066	0.063	0.063	0.064
M	0.065	0.069	0.073	0.076	0.071	0.071
T	0.061	0.065	0.066	0.069	0.063	0.065
R	0.068	0.058	0.056	0.060	0.057	0.060

TABLE B.3 Illuminance Values for New Lenses of a GMC Sierra - 97 Headlamp

Position of Heads	Illuminance Readings (ft-c)					
	1	2	3	4	5	Mean
L	0.150	0.154	0.151	0.157	0.156	0.154
M	0.159	0.164	0.165	0.162	0.160	0.162
T	0.081	0.077	0.079	0.076	0.077	0.078
R	0.067	0.063	0.063	0.065	0.065	0.065

TABLE B.4 Illuminance Values for Degraded Lenses of a GMC Sierra - 99 Headlamp

Position of Heads	Illuminance Readings (ft-c)					
	1	**2**	**3**	**4**	**5**	**Mean**
L	0.014	0.014	0.015	0.015	0.017	0.015
M	0.028	0.024	0.027	0.023	0.024	0.025
T	0.022	0.025	0.030	0.025	0.025	0.025
R	0.015	0.018	0.017	0.018	0.020	0.018

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