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ROADWAY LIGHTING DESIGN METHODOLOGY AND EVALUATION

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Theoretical methods are usually performed for ideal conditions to determine the illuminance and luminance but other design limitations should be considered in the real world. Also the visibility level is calculated by using background and target luminance under ideal conditions. In reality, there are many factors, which are very difficult to predict and include in lighting design equation. Human eye is also a complex device it is difficult to accurately design an outdoor illumination system just simply based on numerous theoretical assumptions. RP-8 is using for theoretical calculation of light distribution on pavement. This calculation method needs to include some correction constant for parameters such as pavement is not level, maintenance for cleaning, aging lamps lamp reflector and refractor is not centered, lamp is off center and tilted, pole is not vertical to the pavement, voltage fluctuation, photodetectors response, ambient temperature factors, reliability of illuminaires, roads crowned, and superelevation.

1. Introduction

Before one can get to the specifics of this topic, one can understand the environmental context of the design solution. Engineers tend to focus on the technology and as such, tend to ignore the salient features of the environmental in which the technology under design must operate. Roadway light is a good example of this mentality. First, engineers and scientist must remember that light is the fastest thing on earth. As a result, it is virtually impossible to predict the actual levels of lighting in a specific area under design. Assume that ambient light is ignored in the design any light that is added to the area under design will merely increase the level of lumination and illumination and make the area brighter than it was designed to be. Ignoring the ambient light is would constitute a conservative and hence desirable design methodology. This seems logical, but it ignores one of the fundamental concepts of visibility and its effect on traffic safety.

With the advent of computer design system of computer modeling of lighting system, it is feasible to calculate Small target Visibility (STV). STV is being proposed as the recommended design practice of the Illumination engineering Society of North America (IESNA) as well as the American National Standard Institute (ANSI).

Small target visibility concepts, basis on assumptions needs to be verified. Technical problems associated with the design procedures need to be investigated to determine extent such problems affect the design. The impact of department of transportation, city street and road departments, utility companies, and construction and maintenance contractors needs to be investigated. The design method needs to be examined to determine if it is practical and worthwhile.

The STV concept, as defined in the proposed ANSI/IES RP-8-1990 (IESNA, 1990), is calculated measure of the visibility of an arbitrary two-dimensional target. The Visibility Level (VL) is an metric used to combine effects of factor listed in RP-8 on a sample target 18 x 18 cm with a diffuse reflectivity of 20%. The target placed perpendicular to the road surface and 83 meter far from the observer. STV is then calculated based on surface reflectivity and orientations with respect to an observer. The results of the calculation are a contrast picture of a small target with respect to the background of the target.

The first successful attempt at developing a visibility criteria was the visibility index (VI) introduced in 1970 by Gallagher, which was base upon the research of Blackwell. Gallagher et al. used the bottom portion of an 18 inch traffic cone which was six percent gray or twenty nine percent white reflectant and established the fact that the calculated visibility of an object was a very good prediction of the distance at which the drivers detected this target. Later in 1977, a study by Janoff showed that the *VI* was a better predictor of nighttime accident rates than were any of the other photometric measures that they evaluated.

In 1989, Adrian from the University of Waterloo, Canada offered a new visibility matrix based upon the works of Blackwell (1946), Aulthorn (1964) and his own. His visibility level (*VL*) was defined as simply the ratio of actual luminance to threshold luminance. The standard target proposed is known as *small target* and the concept is recognized as *Small Target Visibility* (*STV*). The *VL* can be determined using photometers to measure target luminance, pavement luminance and veiling luminance. A predictive computer program then becomes an important factor for a road lighting design. The most recent computer program available is *STV* by Keck (1990) that is being updated as required. Janoff (1993) to compare the target, pavement and veiling luminance performed a study, as well as *VL*s, to actually measured values. This experiment consisted of two different targets. Each target was 7 inch square, and one placed upstream of the closest luminance and one downstream. The targets consisted of three-different reflectance: 5, 30 and 80 %. The results indicated that the predicted values did not match up with measured values. There were significant differences between the target, pavement and veiling luminance. However, Janoff concluded that, perhaps with an accurate r-table for the surfaces under study, accurate reflectance values for the targets, accurate candle power distribution (including depreciation factors) and some derived field factors to account for light reflected from the pavement onto the target, a higher degree of relationship can be derived between measured and predicted values.

In 1997, Adrian, Gibbons and Laura Thomas made an amendment in calculating *STV* and studied the influence of light reflected from the road surface on the target luminance. The reflected light from a total of seventy-two pavement sections was used for each target luminance calculation. Based on the calculation, it was decided that road sections further than 6 multiples of target size from the target need not to be included in the calculation because they contribute less than five percent of the total target luminance. As seen from the calculation the light reflected from the pavement to the target can contribute up to fifteen percent of the total target luminance. This amount will change the *VL* of the target and *VL* can be reduced as much as half the *VL* where no reflection for the pavement is considered.

The appropriate quantity and quality of fixed lighting should be designed to provide comfortable seeing for nighttime drivers. Since the purpose of a roadway lighting system is the improvement of nighttime visual tasks. Visual tasks can be specified in terms of quantities that are measurable in the object space. Some of these quantities are given as:

1. Luminance of the object.
2. Luminance of the background.
3. Contrast.
4. Size.
5. Time.
6. Temporal frequency characteristics.
7. Location relative to the line of sight.
8. Movement in the field of view and non-uniformity of luminance in the object and the back ground.

Visibility of any target is related to the above variables: additionally, cognitive factors such as attention, expectation and habituation will effect recognition of objects. The lighting designer directly considers first four variables that listed above. The designers assumed that both the object (target) and the background luminance are uniformly distributed. And it is assumed that:

- Increasing luminance increases visibility.
- Increasing contrast increases visibility. Given a dark object on a bright background or a bright object on a dark background, seeing improves.
- Increasing visual size of any object increases visibility.
- Given the more time to see a target, likelihood of target acquisition becomes better.

An object may be seen because it differs either in luminance or in color: that is, there may be either a luminance (brightness) contrast or a chromatic contrast. Both types of contrast depend on the reflectance properties of the scene and of the incident illumination and the illumination level.

Stain et al. (1986) show that contrast is generally independent of illumination. Typically a flat plate will exhibit some specularity in its reflection pattern, even if a flat plate is very diffuse it usually does not exhibit a Lambertian deflection pattern (Green et al, 1987). The plate has a specular component plus a Lambertian reflection component.

Contrast, or more accurately luminance contrast, between an object and its adjacent background is defined in several ways (IES Lighting Handbook, Reference Volume, Section 3, 1981). Therefore, the following formula uses for contrast definition for visibility calculation.

$$C = \frac{L_d - L_b}{L_b} \tag{1}$$

Where, C is contras, L_d is luminance of the detail, L_b is luminance of the background, L_g is the greater lumnance, L_t is the lesser luminance.

Equation (1) produces positive and negative contrast values $-1 \le C < \infty$ that are related to luminance values of an object luminance and its adjacent background luminance. If objects are darker than their background, contrast range is between –1 and 0. If objects are brighter than their background, contrast range is between 0 and ∞.

Hall and Fisher (1978) studied the design of roadway lighting system by using empirically derived requirements of light technical parameters such as road luminance, luminance uniformity and glare restriction. In the calculation, 20 x 20 cm target is used within the limited range of contrast. They found that lighting design based on a visibility matrix requires the introduction of simplification. Jug and Titishov (1987) used as a standard 20 x 20 cm target with 18% diffuse reflective surface (Kodak gray card) to conduct their experiments. They found out the fixed lighting has too many transient quantities that are difficult to characterize. In the study, luminance is considered as reflected light in the luminance design standard and illuminance design standard as an incident light only design. Marsden (1976) researched road lighting, visibility and accident reduction numerically and experimentally. They measured disability glare related to veiling luminance, horizontal luminance, and vertical illuminance. They recorded all the information as well as the visual field of the driver on the type. Calculation is also performed for the same field.

Small target specified by RP-8 (IES, 1990) as 18 x 18 cm square with 20% diffuse reflective surface. This target size is accepted because this is the maximum dimension a car can able pass on it without any collision. Freedman et al (1993) proved that the probability of detecting a target strongly depends on its type and that older drivers generally showed a significant lower probability of target detection. Thus, the selection of the target's size, shape and reflective surface can not be arbitrary. Some researchers used different size of target than STV target. Roper (1953) studied visibility matrix by using square target with 40.64 cm^2 area which had a 7.5% reflective surface. Haber (1955) used a large target with a mean linear dimension of 91.4 cm with 15% reflective surface. Waetjen et al (1993) used a target composed of a Landholt ring with a stroke width of 8.7 cm and height of 43.5 cm. Zwahlen and Schnell (1994) used a target with varying reflective surfaces that were 60.96 cm square target and installed 30.48 cm above the surface of the road.

2. Theoretical Small Target Visibility (STV) Calculation Method

In the draft RP-8 (1998), the concept of *Small Target Visibility* (*STV*) has been proposed for roadway lighting design. This came from the assumption that only pavement luminance is not sufficient to see an object. It is necessary to have a difference in luminance of object and background for the object to be visible. This difference in luminance has to be above a certain minimum value for visibility. This difference with respect to a threshold luminance value is termed *Visibility Level* (*VL*). Threshold *VL* values has been excepted by IES Committee, and published in RP_8 as seen in Table 1. *VL* is one of the metrics for *STV*. In the draft RP-8 (1998), recommended design criteria for high-speed roadways is based on luminance.

Table 1. Recommended maintained values of target VL (RP-8 (1988)).

CLASIFICATION OF ROADWAY AREA	STV CRITERIA *WtAvgVL*
Freeway "A"	3.2
Freeway "B"	2.6
Expressway	3.8
Other Roadways-Undivided	3.8
Other Roadways-Undivided	2.6

Theoretical STV calculation has been obtained for a specific lighting situation using the *Keck* software and following the methodology is published in the RP-8. The program (Keck program) calculates theoretical visibility level distribution between the luminaires by assuming ideal conditions on the roadway. For visibility level calculation, only fixed roadway lighting luminaires are considered for the purpose of providing roadway and pedestrian lighting in the calculations (Figure 1). For a roadway lighting installation meets the criteria of RP-8, and the following conditions are assumed and published in RP-8.

1. The observer is located on a line parallel to the centerline of the roadway that passes through the calculation points .
2. The observer located on the line at the distance 83.07 meters from the point.
3. With a 1° downward view from the horizontal, as the defined observation geometry, the fixation line meets the road at 83.07 meters at 1.45 meters eye position from the road.
4. The target is located at the intersection of two grid lines as seen in Figure 2.
5. The pavement's surface is assumed level, uniform, homogeneous dry and to have directional light reflectance characteristics, which are expressed in terms of a reduced luminance coefficient.
6. The target's surface is assumed to be perfectly diffuse, vertical and perpendicular to a line from the observer to the grid point, and the light is reflect in a Lambertian manner.
7. Only fixed lighting luminaires installed for the purpose of providing roadway and pedestrian lighting are considered in the calculations.
8. The distribution of those luminaires is assumed to be representing by a table of luminous intensities.

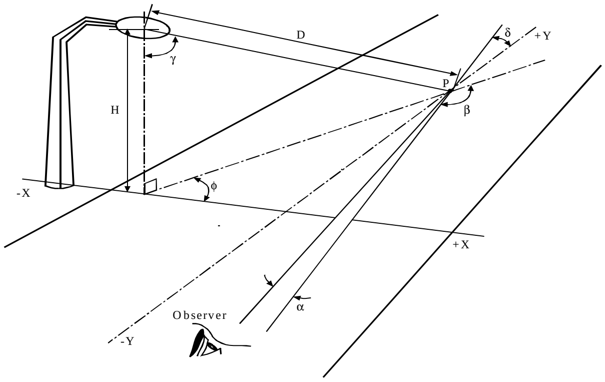

Fig. 1 Single luminaire.

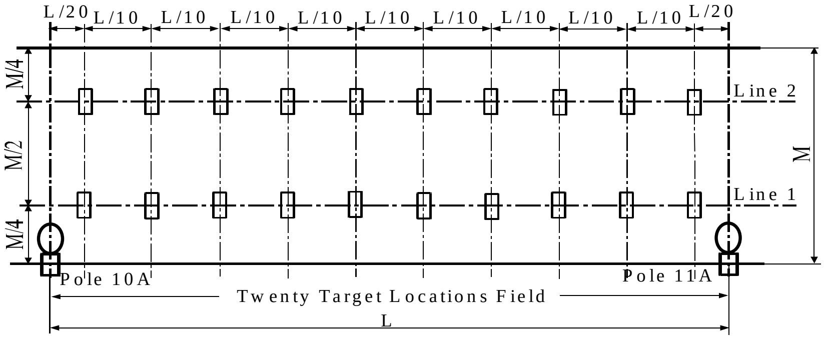

Fig. 2 Target location orientation between the installation.

The above assumptions define the observer location with respect to the calculated point, object (target) and pavement reflection types, object and pavement luminance calculations, and pavement geometric and structural properties. The accuracy of calculations for pavement luminance, and STV not only depends on the above assumptions, but also depends upon the following conditions:

1. The lighting design calculation must include a Light Loss Factor (LLF).
2. Whether or not the photometric data used to determine the candlepower intensity at a particular angle correctly represents the output of the lamp and luminaire.
3. Whether or not the directional reflectance tables (r-tables) provides accurately directional reflectance coefficients of the actual surface.

The visibility level formula is defined in RP-8 and elsewhere, as shown in the following equation:

$$VL = \frac{L_t - L_b}{DL_4} = \frac{L_t - L_b}{L_b} \times \frac{L_b}{DL_4} = C\frac{L_b}{DL_4} \quad (2)$$

RP-8 uses Equation (2) to calculate *VL* distribution between the installation.

3. Illuminance and Pavement Luminance Calculations Method

Illuminance is the measure of the amount of light flux falling on a surface. It is independent of the direction from which the light comes, the type of light source and the type of surface upon which it falls. Mathematically, illuminance may be defined as the luminous flux density per unit area at a point on a surface. Figure 1 shows angle relation to the calculations of illuminance, pavement luminance and light emission from the luminaire.

Luminous Intensity: Unit of the luminous intensity is candlepower (cd) in AS system and candle in SI system. A wax candle has a luminous intensity horizontally of approximately one candle (cp). Luminous intensity is characteristic of the source only and independent of the visual sense of the eye.

Illuminance: One lumen of luminous flux on one square foot produces one foot candle (fc) of illuminance in AS unit or one lumen of flux on one square meter produces one Lux (lx) in SI unit.

$$E_h = \frac{d\varphi}{dA} \quad (3)$$

Where, E_h is horizontal illuminance from one individual luminaire, j is radiant flux and *A* is lighted area. If the luminous intensity (*I(f,g)*) of a light source is known, the horizontal illuminance (E_h) at a distance *D* is given by:

$$E_h = \frac{I(\phi,\gamma) \times Cos(\gamma) \times LLF}{D^2} \quad (4)$$

Where, *I* is intensity at angle g and f, *D* is distance between the luminaire and calculated point (*D= H/ Cos (g)* from the Figure 1, *LLF* is light loss factor**.** Finally, the horizontal illuminance (Equation (4)) yields:

$$E_h = \frac{I(\phi,\gamma) \times Cos^3(\gamma) \times LLF}{H^2}. \qquad (5)$$

The total horizontal illuminance is the sum of the values calculated for all contributing luminaires. Recommended average maintained roadway illuminances are given in Table 2 with respect to roadway and pavement classifications (RP-8).

Roadway Classification Area Classification Pavement Classification, Lux (Foot-candles).

Table 2. Recommended average maintained roadway illuminances (IES Roadway Lighting committee; Proposed American Standard Practice for Roadway Lighting).

R1	**R2, R3**	**R4**		
Freeway	**Commercial**	6 (0.6)	9 (0.8)	8 (0.7)
	Intermediate	4 (0.4)	6 (0.6)	5 (0.5)
	Residential	_	_	_
Expressway	**Commercial**	10 (0.9)	14 (1.3)	13 (1.2)
	8 (0.7)	12 (1.1)	10 (0.9)	
	Residential	6 (0.6)	9 (0.8)	8 (0.7)
Major	**Commercial**	12 (1.1)	17 (1.6)	15 (1.4)
	Intermediate	9 (0.8)	13 (1.2)	11 (1.0)
	Residential	6 (0.6)	9 (0.8)	8 (0.7)
Collector	**Commercial**	8 (0.7)	12 (1.1)	10 (0.9)
	Intermediate	6 (0.6)	9 (0.8)	8 (0.7)
	Residential	6 (0.6)	6 (0.6)	5 (0.5)
Local	**Commercial**	6 (0.6)	9 (0.8)	8 (0.7)
	Intermediate	5 (0.5)	7 (0.7)	6 (0.6)
	Residential	3 (0.3)	4 (0.4)	4 (0.4)

4. Pavement Luminance Calculation Method

Though the design of roadway lighting initiated with the criteria based on horizontal illumination, it was soon realized that pavement luminance and veiling luminance criteria provide a better correlation with the visual impression of roadway lighting quality. Because what we see is not due to the amount of light emitted from the source, but the amount of light that is reflected from the pavement surface.

Luminance is the measure of the amount and concentration of light flux leaving a surface. The luminance of a surface depends on the direction from which the light strikes the surface, the direction from which the surface is viewed and the reflective properties of the surface. The source of radiation is not an issue and it is the luminance the producer of light intensity and reflectivity that controls the magnitude of the sensation that is received by the brain. Luminance at a point P (Figure 1) is proportional to the horizontal illumination at that point. To equate the relationship a proportionality factor *r(*b,g*)* which is called directional reflectance coefficient is introduced.

Luminance: Luminance is the luminous intensity per unit-projected area of a primary (emitting) or secondary (reflected) light source. The SI unit is candela/square meter or a nit (cd/m^2=nit); the AS unit is the Foot-Lambert (3.14 fL=1 cd/f^2).

$$L_b \propto E_h \tag{6}$$

$$L_b = \frac{r(\beta,\gamma)}{MF} \times E_h \tag{7}$$

Where, *r* is reduced coefficient of reflectance at angles g and b and *MF* is multiplying factor used by the *r*-table (often 10,000). Substituting Equation (5) into Equation (7) and multiply with (1/*p*) to obtain SI units (*Lb* = cd/m^2 and *I* = cd), the equation (7) yields:

$$L_b = \frac{1}{\pi} \times \frac{r(\beta,\gamma) \times I(\phi,\gamma) \times Cos(\gamma) \times LLF}{MF \times H_i^2} \tag{8}$$

The total luminance is the sum of the values calculated for all contributing luminaires.

Recommended maintained roadway luminances are given in Table 3 with respect to roadway classifications (RP-8).

5. Target Luminance Calculation Method

Luminance of a target is a function of the vertical illuminance (E_v) from the luminaire in the layout directed toward the target and the directional reflectance of the target (r_t) toward the observer (Figure 1). Figure 1 shows angular relationships between the luminaire, the surface of a vertical target and the observer. The reflectance of the target surface is assumed to be diffuse (Lambertian) for target luminance calculation.

$$L_t = E_v \times r_t \times Sin(\phi), \tag{9}$$

where, L_t is target luminance, E_v is vertical illuminance at point P, r_t is target reflection factor $r_t = R_c \times Cos(1^0)$ and R_c is surface reflection coefficient of a target (for 20%reflective surface R_c=0.2 and for 20% reflective surface R_c = 0.2).

$$E_v = \frac{I(\phi,\gamma) \times Sin(\gamma) \times LLF}{D^2} \tag{10}$$

Table 3. Recommended maintained roadway luminance (IES Roadway Lighting committee; Proposed American Standard Practice for Roadway Lighting).

Roadway Classification	Area Classification	Cd/m^2	$\frac{L_{avg}}{L_{\min}}$	$\frac{L_{\max}}{L_{\min}}$	$\frac{L_v}{L_{avg}}$
Freeway	**Commercial**	0.6	3.5	6.0	0.3
	Intermediate	0.4	3.5	6.0	0.3
	Residential	–	–	–	–
Expressway	**Commercial**	1.0	3.0	5.0	0.3
	Intermediate	0.8	3.0	5.0	0.3
	Residential	0.6	3.5	6.0	0.3
Major	**Commercial**	1.2	3.0	5.0	0.3
	Intermediate	0.9	3.0	5.0	0.3
	Residential	0.6	3.5	6.0	0.3
Collector	**Commercial**	0.8	3.0	5.0	0.4
	Intermediate	0.6	3.5	6.0	0.4
	Residential	0.4	4.0	8.0	0.4
Local	**Commercial**	0.6	6.0	10.0	0.4
	Intermediate	0.5	6.0	10.0	0.4
	Residential	0.3	6.0	10.0	0.4

Where, *TH* is target height, *0.5* is diffuse reflectance factor and *D=(H-0.5xTH)/Cos(g))*. Substituting Equation (10) into the Equation (9) and multiply with (1/p) to obtain SI unit, then the equation (9) yields:

$$L_t = \frac{1}{\pi} \times \frac{I(\phi,\gamma) \times Sin(\gamma) \times Sin(\phi) \times Cos^2(\gamma) \times r_t \times LLF}{(H - 0.5 \times TH)^2} \tag{11}$$

and substituting r_t into the Equation (11), final equation yields:

$$L_t = \frac{1}{\pi} \times \frac{I(\phi,\gamma) \times Sin(\gamma) \times Sin(\phi) \times Cos^2(\gamma) \times R_c \times Cos(1) \times LLF}{(H - 0.5 \times TH)^2} \tag{12}$$

The total luminance from the target surface is the sum of the values calculated for all contributing luminaires.

6. The Roadway Reflectance (r Tables)

CIE (Commission Internationale de I' Eclairage) is the recognized international organization in the field of roadway lighting. CIE successfully introduced roadway classification systems for dry pavements to facilitate luminance calculations at the design stage.

Waldram (1934) compared his brightness patch for the rolled asphalt surface with precoated chipping. He concluded that the old surface gave a much larger brightness patch than the new surface. Finch et al (1967) developed the first direct reading reflectometer for roadway lighting purpose. Until than, reflective characteristics of pavements were evaluated by using visual photometer. This device allowed measuring reflection characteristics of the pavement in tree dimensional.

De Boer and Vermeulen developed the R-system to classify roadway surfaces (pavements) in 1967. It comprises four classes of pavements RI, RII, RIII and RIV, and their corresponding standard *r*- tables R1, R2, R3 and R4. *r*-tables include *r* values (directional reflection coefficients) with respect to b and g angles. Here the observer looks along the Y-axis (Figure 1), while the light source is at an angle b with Y-axis at the origin. The *r*-values are symmetrical about the X-axis. Getting the value of *r (*b,g*)* for a particular point from the *r*-table on the pavement surface and the corresponding I-value from the photometric data one can readily calculate the pavement luminance at a point. The r-tables are used directly in the calculation of STV for background luminance but target luminance appears to come exclusively from the light source with no contribution from the pavement luminance. Table 4 shows the values for *R1* type of pavement. The *r*-table is obtained under laboratory conditions.

7. Veiling Luminance Calculations Method

The luminaire used for roadway lighting emit light directly to the eye of the observer, and as a result produces a reduction in visual performance or a feeling of discomfort. This sensation produced by intense source luminance within the visual field that is sufficiently greater than reflected luminance, to which the eyes are adapted, is known as *glare*. Glare produces a veiling luminance (L_v) which is superimposed upon the retinal image of the object to be seen. This alters the apparent brightness of the object and the background against which it is viewed and causes a reduction in visual performance. L_v can be calculated by using the following empirical formula derived for one single luminaire.

$$L_v = \frac{K}{\theta^n} = \frac{10 \times E_v}{\theta^n} \qquad (13)$$

$$n = 2.3 - 0.7 \times Log_{10}(\theta) \;\; \text{for } \theta < 2$$

$$n = 2.0 \qquad\qquad \text{for} \theta \geq 2$$

Where, E_v is ertical illuminance in the plane of the pupil of the observer's eye (Equation (10)) and θ is seen if Figure 3. Total veiling luminance is the sum of the veiling luminance of all of individual contributing luminaires.

8. Light Loss Factor

The photometric data that is used in calculating illumination or luminance is obtained under laboratory conditions. But in the field, the performance of the luminaires deteriorates. Therefore, a multiplying factor, known as Light Loss Factor (*LLF*), is used in lighting calculations. This *LLF* is composed of

Table 4. ***r*-table of *r* values for standard *R1* type of pavement (All values have been multiplied by 10,000).**

6 tan Y	0	2	5	10	15	20	25	30	35	40	45	60	75	90	105	120	135	150	165	180
0.00	655	655	655	655	655	655	655	655	655	655	655	655	655	655	655	655	655	655	655	655
0.25	619	619	619	619	610	610	610	610	610	610	610	610	610	601	601	601	601	601	601	601
0.50	539	539	539	539	539	539	521	521	521	521	521	503	503	503	503	503	503	503	503	503
0.75	431	431	431	431	431	431	431	431	431	431	395	386	371	371	371	371	371	386	395	395
1.00	341	341	341	341	323	323	305	296	287	287	278	269	269	269	269	269	269	278	278	278
1.25	224	224	224	215	198	180	171	162	153	148	144	144	139	139	139	144	148	153	162	180
1.75	189	189	189	171	153	139	130	121	117	112	108	103	99	99	103	108	112	121	130	139
2.00	162	162	157	135	117	108	99	94	90	85	85	83	84	84	86	90	94	99	103	111
2.50	121	121	117	95	79	66	60	57	54	52	51	50	51	52	54	58	61	65	69	75
3.00	94	94	86	66	49	41	38	36	34	33	32	31	31	33	35	38	40	43	47	51
3.50	81	80	66	46	33	28	25	23	22	22	21	21	22	22	24	27	29	31	34	38
4.00	71	69	55	32	23	20	18	16	15	14	14	14	15	17	19	20	22	23	25	27
4.5	63	59	43	24	17	14	13	12	12	11	11	11	12	13	14	14	16	17	19	21
5.00	57	52	36	19	14	12	10	9.0	9.0	8.8	8.7	8.7	9.0	10	11	13	14	15	16	16
5.50	51	47	31	15	11	9.0	8.1	7.8	7.7	7.7										
6.00	47	42	25	12	8.5	7.2	6.5	6.3	6.2											
6.50	43	38	22	10	6.7	5.8	5.2	5.0												
7.00	40	34	18	8.1	5.6	4.8	4.4	4.2												
7.50	37	31	15	6.9	4.7	4.0	3.8													
8.00	35	28	14	5.7	4.0	3.6	3.2													
8.50	33	25	12	4.8	3.6	3.1	2.9													
9.00	31	23	10	4.1	3.2	2.8														
9.50	30	22	9.0	3.7	2.8	2.5														
10.0	29	20	8.2	3.2	2.4	2.2														
10.5	28	18	7.3	3.0	2.2	1.9														
11.0	27	16	6.6	2.7	1.9	1.7														
11.5	26	15	6.1	2.4	1.7															
12.0	25	14	5.6	2.2	1,6															

Q0 = 0.10: S1 = 0.25: S2 = 1.53

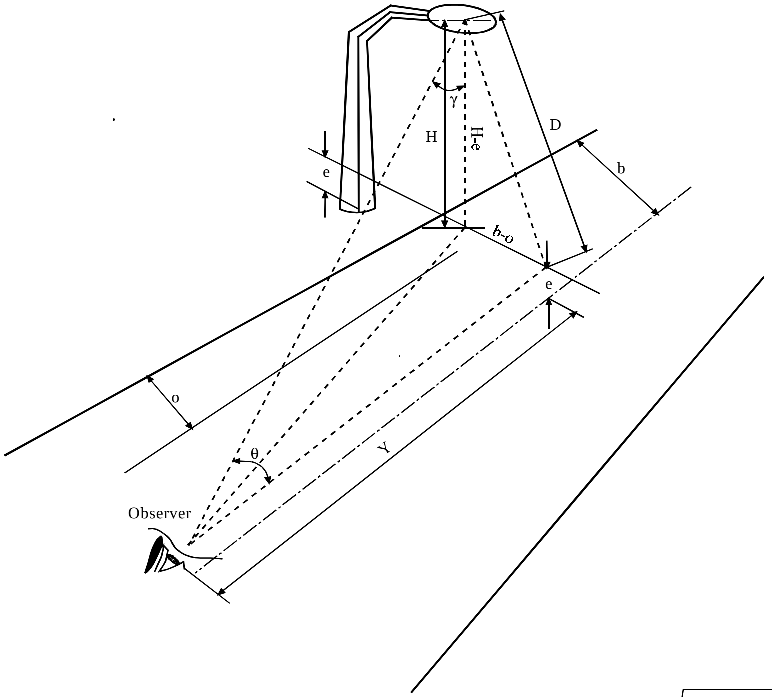

Fig. 3 Angular relationship for veiling luminance calculation $D = \sqrt{(H-e)^2 + (b-o)^2}$ **.**

several separate factors, each of which is controlled and evaluated separately. Broadly *LLF* is divided into two categories. One is the *Maintenance Factor*, which is time dependent, and the other is the *Equipment Factor*, which does not depend on time. *Maintenance Factor* takes into account dirt accumulation on luminaire surface, lamp lumen depreciation and maintenance procedures. *Equipment Factor* relates mostly to the characteristics of the specific equipment selected. It takes into account factors such as ambient temperature, voltage fluctuation, ballast variation, change in physical surroundings and surface depreciation resulting from adverse changes in metal, paint and plastic components which produce reduced light output.

9. Small Target Calculation Visibility Steps

Contrast definition as given before is a combination of object and background luminances. The Small Target Visibility definition uses the contrast definitions, but STV always assumes targets are darker that their background and uses Equation (2) for visibility level calculation.

Until this point, target luminance and background luminance calculation methods are given, then visibility of the target (object) can be able to calculate. At this calculation stage, calculation methods of target (Equation (12)) and background luminance (Equation (8)) already explained. Veiling luminance calculation method is also given. Equation (2) shows that *VL* is a ratio with contrast, background luminance and DL_4. After this calculation stage, DL_4 calculation steps will be introduced step by step. All these steps will show what is the function of $DL_{4.}$ Before starting to calculate DL_4, lets make some assumption as follow:

1. The observer is 60 years old people with normal eyesight whose fixation time is 0.2 seconds.
2. The target is an 18x18 cm square flat surface perpendicular to both the road surface and the observer's line of sight.
3. The target reflects light in a Lambertian manner with a reflectance of 50%.

<u>*Step 1*</u>: Calculate adaptation luminance.

$$L_a = L_b + L_v$$
$$LL_a = Log_{10}(L_a)$$
$$A = \arctan\left(\frac{\text{Target Size}}{\text{Distance Observer to Target}}\right) \times 60$$

Where, L_a is adaptation luminance and A is visual angle in minutes.

<u>*Step 2*</u>: Calculate the sensitivity of the visual system as a function of adaptation luminance.

$\underline{L_a \geq 0.6}$

$$F = \left[Log_{10}\left(4.1925 \times L_a^{0.1556}\right) + \left(0.1684 \times L_a^{0.5867}\right)\right]^2$$
$$L = \left(0.05946 \times L_a^{0.466}\right)^2$$

$$\underline{L_a > 0.00418 \text{ and } L_a < 0.6}$$

$$F = 10^{\left\{2\times\left[\left(0.0866\times LL_a^2\right)+\left(0.3372\times LL_a\right)-0.072\right]\right\}}$$

$$L = 10^{\left\{2\times\left[\left(0.319\times LL_a\right)-1.256\right]\right\}}$$

$$\underline{L_a \le 0.00418}$$

$$F = 10^{\left[\left(0.346\times LL_a\right)+0.056\right]}$$

$$L = 10^{\left[\left(0.0454\times LL_a^2\right)+\left(1.055\times LL_a\right)-1.782\right]}$$

<u>Step 3</u>: Calculate some constant to obtain DL_1 using the following equation.

$$B = Log_{10}\left(A\right) + 0.523$$

$$C = Log_{10}\left(L_a\right) + 6.0$$

$$AA = 0.36 - \frac{0.0972\times B^2}{B^2 - 2.513\times B + 2.789}$$

$$AL = 0.335 - \frac{0.1217\times C^2}{C^2 - 10.4\times C + 52.28}$$

$$AZ = \frac{V\times\left(AA^2 + AL^2\right)}{2.1}$$

$$DL_1 = 2.6\times\left(\frac{V\times F}{A} + V\times L\right)^2$$

<u>Step 4</u>: Calculate the M from the following one of three empiric equation. Then determine the value of a negative contrast adjustment factor (*FCP*). If LL_a is less than -2.4, *FCP* is not accurate.

$$\underline{LL_a > -2.4 \text{ and } LL_a < -1.0}$$

$$M = 10^{\left(-10^{-\left[0.075\times\left(LL_a+1\right)^2+0.0245\right]}\right)}$$

$$\underline{LLa \ge -1.0}$$

$$M = 10^{\left(-10^{-\left[0.125\times\left(LL_a+1\right)^2+0.0245\right]}\right)}$$

$\underline{LL_a \le -2.4}$

$FCP = 0.5$ (TGB and FCB need not be calculated)

$$TGB = -0.6 \times L_a^{-0.1488}$$

$$FCP = 1.0 - \frac{M \times A^{TGB}}{2.4 \times DL_1 \times \frac{AZ+2}{2}}$$

Step 5: Adjust DL_1 in accordance with the observation time which is a constant, 0.2 seconds.

$$DL_2 = DL_1 \times \frac{AZ+T}{T}, \text{ where } T \text{ is observation time.}$$

Step 6: Calculate the adjustment for the age of the observer and then adjust DL_2 accordingly. In the calculations the age is always 60 and therefore adjustment is always 1.

$$Age \le 64 \Rightarrow FA = \frac{(TA-19)}{2160} + 0.99$$

$$Age > 64 \Rightarrow FA = \frac{(TA-56.5)}{116.3} + 1.43$$

$$DL_3 = DL_2 \times FA$$

Step 7: Calculate the adjustment if the target is darker than the background (negative contrast).

$$L_t < L_b \Rightarrow DL_4 = DL_3 \times FCP$$

$$\text{otherwise} \quad DL_4 = DL_3$$

Step 8 (Final Step): Calculate Visibility Level (*VL*).

$$VL = \frac{L_t - L_b}{DL_4}$$

Summary of Data: Large *VL* values are not counted as heavily in the calculation of the summary values used in Table 7. In order to compensate for this saturation in recognition times (0.2 seconds). The calculated summary values are described as follow.

1. Negative VL values are converted to positive and calculate RWVL values.

   $$RWVL = 10^{[-0.1 \times ABS(VL)]}$$

2. Average the *RWVL* values.
3. Convert the averaged *RWVL* values to weighted average *VL (WtAvgVL).*

$$WtAvgVL = -10 \times Log_{10}(RWVL)$$

10. Small Target Visibility Level Calculation

VL calculation method is completed at this point. Here, application of the method to an object will be introduced. Roadway lighting designers assumed an object (target) is always darker that the background as seen in Figure 4. This assumption is always produce negative visibility or contrast for an object as defined in the previous section ($C = (L_t - L_b) / L_b$).

As seen from the visibility equation, target and background luminances should be known to obtain the visibility of the target. The background and target luminances are calculated using Equations (8) and (12), respectively. Target luminance is calculated at the middle of the target and background luminance is calculated at the immediate middle points of the upper and lower boundaries of the target as seen in Figure 2. L_{b1} and L_{b2} (Figure 5) are separately calculated using equation (8) and the pavement luminance (L_b) is calculated by taking arithmetic average of L_{b1} and L_{b2} as ($L_b = (L_{b1} + L_{b2})/2$)). Where, L_{b1} is background luminance at the upper boundary of the target and L_{b2} is background luminance at the lower boundary of the target (Figure 5).

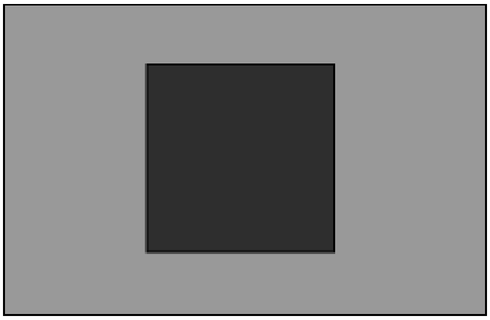

Fig. 4 STV assumption for contrast distribution.

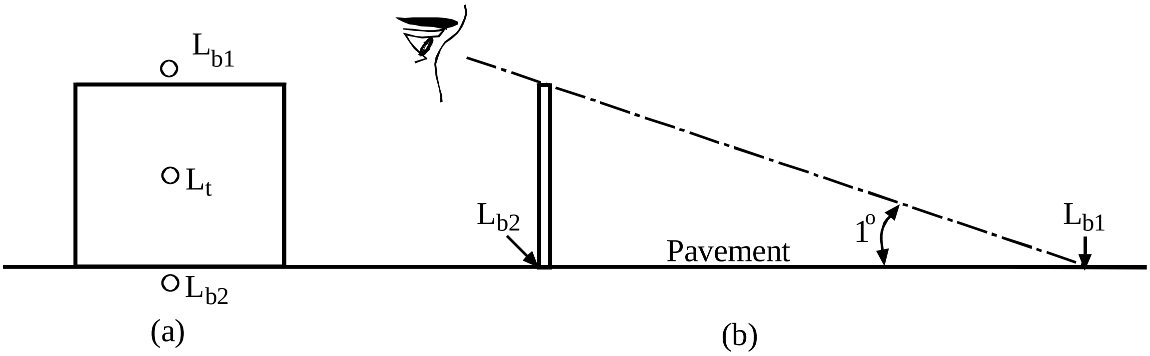

Fig. 5 Luminance calculation locations on the target; a) front seeing , b) side seeing.

11. Small Target Visibility Program

The Roadway Lighting committee of the IES decided to create a new criterion for designing and evaluating the roadway lighting system. The decision was done by committee action. The computer program, developed by Merle E. Keck, used in calculating the visibility Level of the lighting systems. In this program, he used the target, observer, target locations and dimensions as provided by the IES Roadway Lighting Committee in its 1990 proposed revision of the ANSI/IES RP-8.

The program keeps the observer age (64 years), the observation time (0.2 seconds) and the size of the target (18x18 cm flat target) constant for all calculations. The compute program calculates the visibility level of a set of small target, in terms of the adaptation level, contrast and glare produced by the lighting system. Twenty target locations (grid points) are created between two installations. Targets are located at the intersection points of the grids. The Visibility Level (*VL*) of each target is evaluated with the observer location at the same distance and angle relative to each target. The program also calculates waited average visibility level. This prevents the average from being distorted by a few targets having an excessively high or low value. Output of the program includes *VL* values for each individual target and pavement luminance values for each target locations (grid points).

The program is used to calculate *VL* values for our experimental field. In the field, the roadway lighting system is already designed. In this portion of the study, the roadway lighting design properties (geometric, pavement and luminaire) are loaded to the program to obtain theoretical *VL* values distribution between the installation. As an example, using the Keck program will perform the following exercise for roadway light application.

1. Luminaire photometric data = Ge7318.ies (manufactured provide)
2. Initial Lumen = 27500 lm
3. Pavement type = R3
4. Road wide = 12 ft
5. Number of luminaire = 4
6. Distance between the installation in the target location area = 147 ft.

The above values and also some additional values are loaded to the computer program to obtain visibility level values for the assumed exercise. This program was run for 20% and 50% reflective surface target with four different types of pavements. For each individual run, all the loaded values were kept constant except target surface reflection value and pavement. The results of the program (visibility level, *VL*) were plotted and also compared.

11.1. 20% Reflected Target

The program calculates all negative visibility values between the installation for 20% reflective surface target with four different pavements. Taking absolute values of the program outputs performed the plots.

Table 5. Arithmetic average of *VL* values for 20% reflective target.

R1		R2		R3		R4	
Line 1	Line 2	Line 1	Line 2	Line 1	Line 2	Line 1	Line 2
9.58	9.49	8.63	7.75	9.34	7.87	10.58	8.7

20% Target with Four Different Pavements:

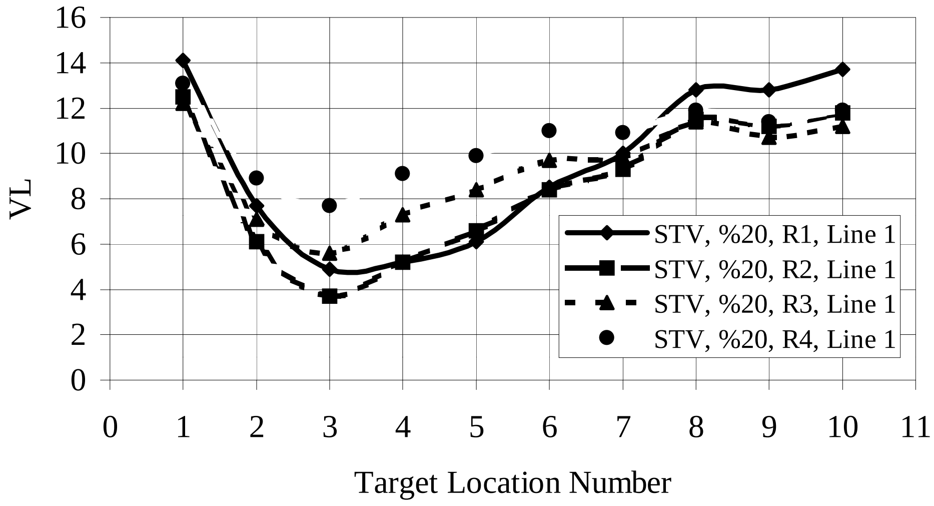

Fig. 6 Visibility level distribution for four different pavements on the line 1 between the installations.

11. 2. Visibility Level Comparison

The program calculates arithmetic average of ten *VL* on lines 1 and 2 (Figure 2). This calculation performed for 20% reflective surface target with four different pavement surfaces. The average values of VL is presented in Table 5.

As seen from Table 5, arithmetic average value of the *VL* values for the pavement types *R1*, *R2*, *R3* and *R4* on the line 1 is 9.58, 8.63, 9.34 and 10.58 (Table 5), respectively. According to the average values and Figure 6, *R4* type of pavement is provide the best visibility task for 20% reflective target, *R1* and *R3* are second and almost the same and *R2* is the worst pavements to create visibility level values for 20% target on the line 1. But according to RP-8 recommended *VL* values, even minimum *VL* value for *R2* pavement is still greater than the recommended *VL* value on line 1. It means that if the object has 20% reflective surface, it is visible on line one for four different pavements.

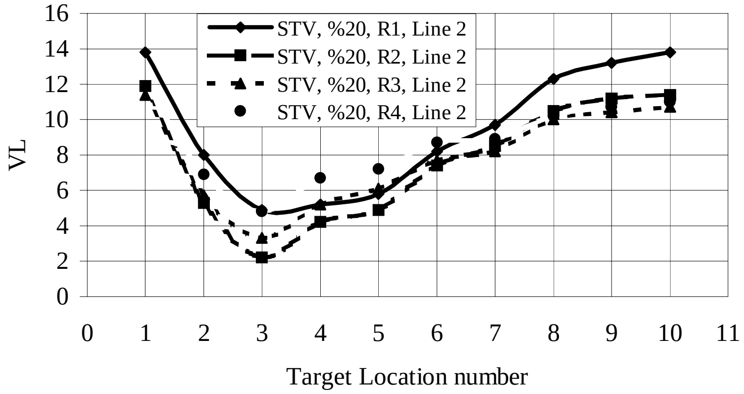

Fig. 7 Visibility level distribution for four different pavements on the line 2 between the installations.

Arithmetic average of the *VL* values for the pavement types *R1, R2, R3* and *R4* on the line 2 is 9.49, 7.75, 7.87 and 8.7 (Table 5), respectively. According to the average values and Figure 7, *R1* type of pavement is the best, *R4* is the second and *R2* and *R3* are the worst and almost the same pavements to create visibility level values for 20% target on the line 2. As seen from Figure 7, Pavement R2 and R3 have the lowest VL value at the target location 3, which is less than the recommended *VL* values. It means that the target is not visible at the target location 3.

From Figure 6 and 8, *R4* pavement is provides better *VL* values on the line 1 but it provides second good *VL* values on the line 2. On the line 2, *R1* type of pavement provides the better *VL* values. *R1* and R3 type of pavements provide second good *VL* values on the line 1 but *R3* is the worst pavement to provide VL values on the line 2. *R2* type of pavement is the worst pavement to provide *VL* values for 20% reflective target. As a result, *R1* and *R4* pavements are the best pavements to create enough visibility for 20% reflective target.

11.3. Video Images

Video images are performed at the same location on the roadway on which theoretical *VL* values are obtained.

As seen from Figure 8 and 9, the target is not visible at the target location 1 and 3. But according to the theoretical calculation target is visible at the target location 1 and it is not visible at the target location 3 (Figure 7). The difference between the theoretical and the experimental results are because of the assumption for theoretical calculation. What are the real conditions, theoretical calculation does not consider.

Theoretical methods are usually performed for ideal conditions to determine the illuminance and luminance but other design limitations should be considered in the real world. In this problem, there are many geometric and environmental factors that does not include by the theoretical method.

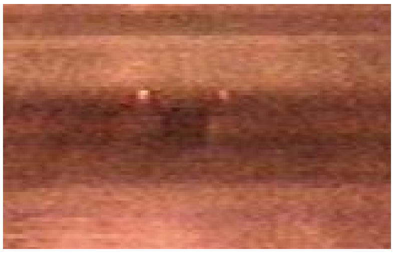

Fig. 8 Video image of the target at target location 1 on line 2.

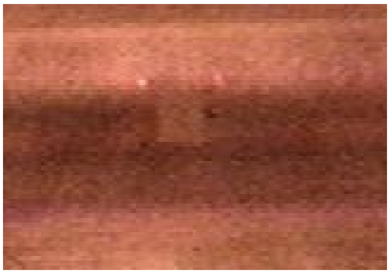

Fig. 9 Video image of the target at target location 3 on line 2.

12. Errors in Calculation

VL calculation needs to improve by adding the following correction factors into the luminance and illuminance formulations.

12.1. Super Elevation Correction

In general, a typical roadway has a luminaire pole installed fifteen feet from the outside edge of pavement. Two basic luminaires with 250-Watts and 400-Watts high-pressure sodium (HPS) used on highways around the world. Mounting height of the poles is 40 ft for 250-Watt lamp and 50 ft for 400-Watt lamp. Both luminaire poles have 8 ft mounting arm.

A typical highway has 2% crown along the straight stretch and 8% superelevation along the curve as seen in Figure 10. The transition stretch between the straight and curve has an average 2% crown for the inner lane of the curve and 0%crown for the outer lane at its beginning. As seen from the figure, roadway surface is not parallel to the horizontal line along the straight stretch and curve. Therefore, luminance of the road surface (pavement) should be correlated by the cosine of the angle between the vertical axis and the slope of the road surface, and also between vertical axis and crown of the road surface.

12.2. Aging of Lamp

Manufacturer gives aging of lamps; however, the lamp evaluation does not taking in account accurately the several thousands hours of usage. Lighting calculations include the light loss factor (maintenance factor) (LLF). LLF only considers mounting errors. In reality, there is several factors effect the LLF such as the time, temperature, and voltage variations, dirt accumulation on the luminaire surfaces, lamp filament deterioration, maintenance procedures, equipment and ballast variation. Some of the above factors are beyond the control of the lightning manufactures such as voltage regulation, weather, emission control of the atmosphere.

Tiny vapor is deposited on the glass container walls when a filament lamp burns. The time dependent depreciation effects should be taken in account in the initial design. Regular maintenance is important regarding the energy conservation and it is covered by the maintenance factor (MF). Lamp intensity depreciation is available from the manufactures tables and graphs. The lamp lumen depreciation (LLD) is determined based on the elapsed time per year. Saltner (1960) studied the aging test of luminaires. He showed that the maximum spread was up to ±6% for fluorescent lamps.

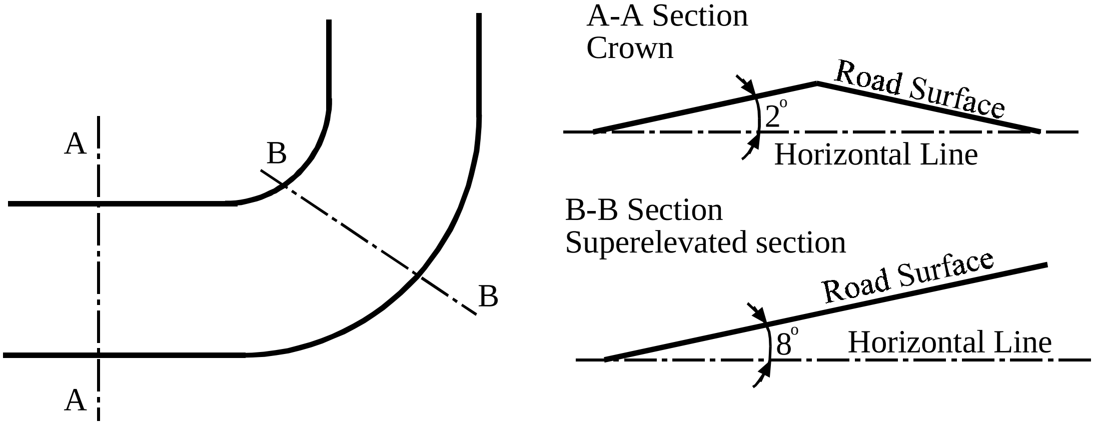

Fig. 10 Typical highway.

12.3. Lamp Reflector and Refractor

The manufacturer gives the lamp reflector and refractor tolerances. Each manufacturer part has its variation in the aluminum material from the light source of which it is made despite manufacturing specifications require an accurate specular aluminum reflector sheet. Even a small degree of specularity can significantly influence the performance. Franklin (1974) reported that the total efficiency difference is up to 9%.

12.4. Luminaire Dirt Depreciation

Dirt accumulated on a luminaire causes a loss of the light output. It has been experimentally seen that the output loss is a nonlinear function. The RP-8 proposed standard describes five categories of the ambient environment. Assuming about 4000-4300 hours of usage a year and life cycle of 8000 hours, the luminaire dirt depreciation has a factor of 0.9 to 0.7 or even less for moderate ambient environment.

Studies in Texas Tech University show that clean lenses provide an average of 30 percent better illuminance than the luminaire with original lenses while the new luminaires approximately provide average of 45 percent better illuminance than the original luminaire with clean lenses. The new 250 watts luminaires approximately resulted in an average of 80 percent better illuminance than the original luminaire with original lenses. The STV measurements demonstrate the significance change in luminance, illuminance, and visibility before and after cleaning the unit. Assuming an average of 30% change (factor 0.3) is a very conservative assumption for luminaire dirt depreciation.

12.5. Lamp off Center and Tilted

Tilt is the angular position of the luminaire around an axis through the light center and along the 90-270 degree horizontal axis. When the luminaire is level, the tilt is zero degrees. On roadway mounted units the tilt was as high as ±5° as in Figure 11. The luminaire can off center. The lateral displacement can be larger than is the arc displacement in halogen lamps. Franklin (1974) show that the lamp data sheet usually shows a ±3% variation (Figure 11). Lewin (1988) show that a one degree of an incidence angle will cause a 5% error at 70 degrees and 10% at 80 degrees. Consultation with TxDOT brought out the high-pressure sodium lamps also performed with at least ±3% variation in specific direction.

12.6. Voltage Fluctuation and Lamp’s Ballast

Utility company of the American National Standards Institute (ANSI) permits the flux lamp to fluctuate by ±10% for mercury lamps, ±20% for high-pressure sodium (HPS) lamps and ±15% for metal halide lamps. Generally the voltage changes in RMS terms and influences the luminous output and the ballast performance.

According to TxDOT lighting engineers, a good practice is to assume that the utility power fluctuates up to ±6%. The lamp ballast is used to improve the power factor of the illumination unit and to lower the power surges to a utility system. The 92.5% is the minimum that the lamp output can be lower with the Certified Ballast Manufactures Associations (CBM) ballast. Generally, three basic electromagnetic HPS ballast types are using; non-regulating, lead-type regulators and lag-type regulators. Non-regulating ballast produces large changes in light output as line voltage changes such as a 1% line voltage change will cause a 2.5% light output change. Lead-type regulating ballast changes light output by 1.5% for 1% voltage change. Lag-type regulating ballast changes light output 0.8% for 1% voltage change. These parameters are assumed when a new system is running under nominal conditions such as a proper match between the luminaire type and its rating with matching ballast, and unit is maintained through the life of the lighting system. As a result, the light output can change up to ±9% for ±6% voltage fluctuation.

12.7. Photodetectors Response

The actual lighting measurements cannot be neglected while one determines the design error. According to Dr. Werner (consulting with him), generally the spectral sensitivity of photodetectors is different of our eye sensitivity. At night human eye is more sensitive to lower frequencies, blue light, detected by rods, while during the day the cons detect mostly the red light. The standard detector does not have the matching curve for a human eye. The calibration is established by comparing the detector to a known source while adding color filters. When matched, the error is believed to be no more than ±3%.

12.8. Lamp Output versus Temperature

The mercury lamps are temperature dependent because the output of a fluorescent lamp depends on the ambient temperature vs. the coldest spot of an arc. However, they still have transparent arc tube, and the own arc is semitransparent to its own radiation. The IES recommends for laboratory conditions to held temperature ±2°F, then the 5 percent output range can be accomplished. Lewin (1988) show that the mercury lamp is calibrated for 25 °C ambient temperature and everything above or below, the luminous output decreases or increases about 1 – ½ percent per 1°C, and HPS lamps are opaque to their emitted light and the power is absorbed by the arc tube, evaporated luminous material and the end caps. This effect in practice must be pinpointed to specific reflector design. In this publication it has been assumed that a difference in luminous flux will not be higher than 5%.

12.9. Luminous Detectors

In illumination design, the lamps are treated with a high level of respect and enthusiasm. What has been usually left behind is the meter calibration process. Kostkovski (1977) estimates up to 4.1% fluctuation of results relative to SI unit. The laboratory “expensive” light meters are certified to about ±5% by Lewin (1988). As stated above, the NBS value is much tougher. Kostkovski (1977) show that the inexpensive portable light meters are not accurate with the spec error of up to ±15%.

12.10. Burned Illuminaire

It is a common factor to assume that some of the illumination units are not functioning. After consulting with TxDOT lighting engineers, it is a good engineering practice to assume that 96% of functioning desirable, 94% is acceptable and 92% tolerable.

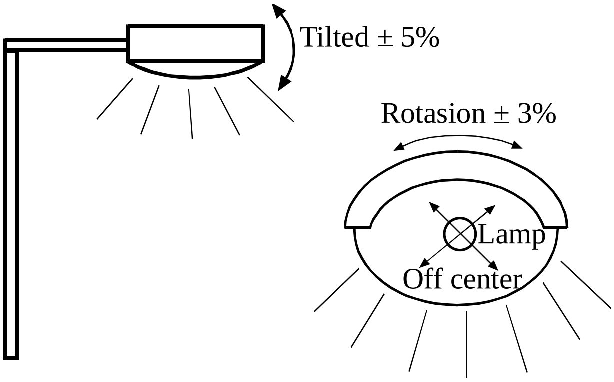

Fig. 11 Lamp off center and tilted.

13. Conclusion

As seen from theoretical calculation and the video images, the visibility level calculation method needs to be improve based on the experimental investigation. There are a lot of parameters, which are ordered above, the theoretical calculation does not include. These parameters are very difficult to plug in the theoretical equations in real world.

These factors decrease the lamp unit performance by reasonable percent and naturally they decrease the object visibility. Roadway lighting design method (RP-8) needs to be improving by including some of the factors ordered above. Those factors can be including into luminance and illuminance formulas as a constant after some experimental study done for each item.

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