

Does Roadway Luminance Correlate with Visibility Metric of CIE 19/2?

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The latest mathematical model for predicting visibility of an object was published in 1980 by the International Commission on Illumination (CIE) as technical report 19/2. It is based on a visibility index (VI), which is defined as the product of equivalent contrast, relative contrast sensitivity, disability glare factor, and transient adaptation factor and is modified by the reciprocal of the constant 0.0923. The visibility of a small square target (18 cm on a side) with a totally diffusing surface when viewed against an R3 roadway surface background has been evaluated by using this model. The Roadway Lighting Committee of the Illuminating Engineering Society of North America has just approved a new standard practice for roadway lighting. The design criteria are based on two equally acceptable metrics—pavement luminance or illuminance. The decision of which to use is left to the discretion of the designer or specifier. This paper evaluates the correlation between the pavement luminance criteria and the visibility model (VI) of CIE 19/2.

The Roadway Lighting Committee (RLC) of the Illuminating Engineering Society of North America (IESNA) on August 7, 1982, approved a revision to the Standard Practice for Roadway Lighting (ANSI RP-8). This revision incorporates design criteria based on pavement luminance, luminance uniformity, and veiling glare as the preferred and equally acceptable metric for roadway lighting. The previous edition (1) was based solely on horizontal illuminance.

The objective of fixed roadway lighting and automobile headlights is to make visible the objects and cues on the roadway to permit the driver to evaluate the visual scene for the purpose of driving safely.

In 1980, the International Commission on Illumination (CIE) published report 19/2 (2), which defines a mathematical model for describing the influence of lighting parameters on visual performance.

The purpose of this paper is to evaluate the correlation between the visibility model of CIE 19/2 and the luminance performance criteria proposed in the IESNA-recommended standard practice.

THE TARGET

To apply the visibility model of CIE 19/2, we need a target to simulate an object on the roadway to be detected by the driver. A variety of targets, from simple discs to three-dimensional objects of various sizes and shapes, have been used in different roadway lighting research projects. For this evaluation, a flat two-dimensional target (18 cm on a side) with a perfectly diffusing surface has been chosen because it was desired to have the following attributes:

1. A simple flat target whose brightness is easy to predict;
2. A target of about 4 minutes in visual size at 150 m, since much of CIE 19/2 was based on a 4-minute target; and
3. A size and shape that would make it easy to produce semirealistic objects by combining a number of the 18-cm targets.

VISIBILITY MODEL

One of the earliest applications of a visibility model for roadway lighting was developed by Gallagher (3, p. 85). He called the visibility metric a visibility index (VI), which was defined as

$$VI = C \cdot RCS \cdot DGF \quad (1)$$

where

C = contrast,
RCS = relative contrast sensitivity, and
DGF = disability glare factor.

CIE 19/2 also used the term visibility index to define the purely physical measures of visibility. Their formula is slightly different:

$$VI = (C \cdot RCS \cdot DGF \cdot TAF) / 0.0923 \quad (2)$$

where TAF is the transient adaptation factor.

In this paper, Equation 2, which is from CIE 19/2, was used. The terms C, RCS, DGF, and TAF are as defined in CIE 19/2. (Note, the definition of the terms C, RCS, and DGF are the same for both Equations 1 and 2.) The computer program used to develop these values was intended to include TAF in the calculations. However, some problems arose as to how large an area to use as the background in the glance at either the lightest or darkest roadway areas just prior to fixation on the target. Some exploratory calculations gave a TAF between 0.97 and 1.0, regardless of the interpretation used. Therefore, it was decided to set TAF equal to 1.0 (4, p. 151) for all the calculations of VI, i.e.,

$$VI = (C \cdot RCS \cdot DGF) / 0.0923 \quad (3)$$

This is the formula used in all visibility calculations for this paper. The physical variables required for the parameters of VI are as follows:

Lt = luminance of task,
Lb = luminance of the background around the task,
d = task size (angular minutes),
A = age of the observer (years), and
Lv = veiling luminance

ROADWAY GEOMETRY AND ANALYSIS PROCEDURE

Figure 1 shows the elevation and plan view for a typical lighting system as used in this study. The observer is located in a vehicle at 1.45-m eye height and (headlights off) one-quarter of the lane width from the left edge of the lane. The target (task) is always located on the ocular line of sight that is always parallel to the lane width markers and curb. The fixed lighting is always arranged so that the first unit is on the same transverse roadway line as the observer and on his or her left

Figure 1. Typical lighting system.

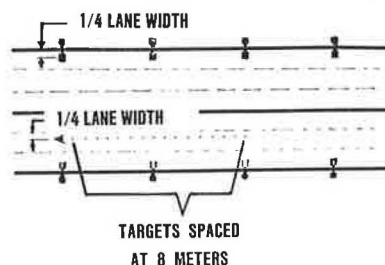
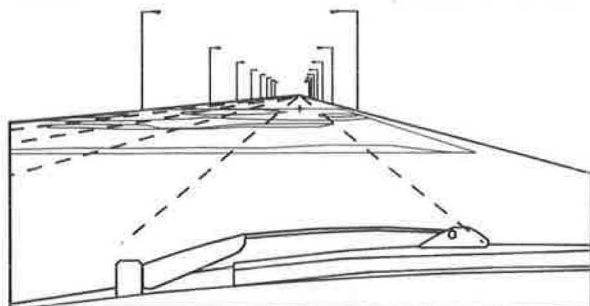


Figure 2. Driver's view of road.



side. The luminaire overhang is always one-quarter of the lane width. The roadway pavement is considered to have the directional reflectance characteristics of a CIE R3 pavement (5).

The targets are always spaced down the road at 8-m intervals. Because the target is relatively small, one location on the target was used to calculate L_t and one location on the pavement (target removed) to calculate L_b (target shadow ignored). Pavement luminance, both when used as a background for the target and when expressed as an average luminance over the entire roadway (L_{ave}), was calculated by the method recommended in the new proposed Standard Practice for Roadway Lighting (RP8). Veiling luminance for the stationary observer is the maximum found in any lane as the observer is moved through the luminaire cycle and is calculated as recommended by the RLC in RP8. Figure 2 shows the typical lighting arrangement from a driver's viewpoint.

Following are the variables of the typical lighting arrangement and luminaire characteristics used in the analysis:

1. Target reflectance,
2. Observer and target locations,
3. Lamp lumens,
4. Luminaire spacing,
5. Luminaire mounting height,
6. Photometric distribution, and
7. Opposite versus staggered.

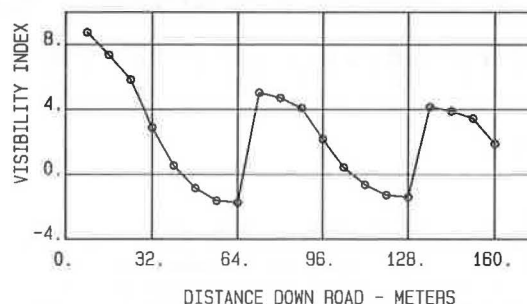
As can be readily understood, there is an infinite number of combinations of the variations listed above. It would be equally impossible to cover the impact of all of these variations in this paper. The reasoning used to select the specific details investigated to date is explained next.

This paper is devoted to exploring the visibility of multiple targets as the application techniques commonly used to improve the level and uniformity of luminance and illuminance are applied. It is hoped that this will give a better understanding of the possible and probable detection of a target that might suddenly occur ahead of the observer out to a distance of 160 m, which is well beyond the distance required for safe stopping at 88.5-km/h driving speed. The target is in the same lane as the observer in all cases, since it is felt that the driver will take no drastic evasive or braking action on seeing a stationary target in another lane. Also, the analytic model for CIE 19/2 is not useful for predicting the visibility of an object in motion.

Once such a target occurs, the observer, who is really in a moving vehicle, then approaches the target at his or her driving speed. As the driver does so, the visibility of the target will vary due to the following facts:

1. The targets angular size increases.

Figure 3. Typical VI.



2. L_t will increase as the observer's headlights approach the target. This may increase or decrease contrast, depending on whether the initial detection occurred under positive or negative contrast conditions.

3. The background against which all or part of the target is seen will change.

4. L_v will increase and decrease in a rhythmic cycle as the observer passes through the fixed lighting system.

CIE 19/2 as well as most other work in lighting has defined contrast as follows:

$$C = |(L_t - L_b)/L_b| \quad (4)$$

Because it is felt that item 2 above is a very important factor in explaining the ability to detect an approaching target, the sign of the contrast (+ or -) was maintained:

$$C = (L_t - L_b)/L_b \quad (5)$$

Carrying this into the VI calculation gives the possibility of either a positive or negative VI.

DATA PRESENTATION AND DISCUSSION

The same geometric arrangement is used as the base for comparison throughout the study. The list below gives the particulars for this arrangement:

1. Road width = 22 m,
2. Number of lanes = 6,
3. Arrangement = opposite,
4. Mounting height = 10.67 m,
5. Spacing = 64 m,
6. Overhang = 0.92 m,
7. Target location = lane 5,
8. Target reflectance = 20 percent,
9. Target spacing = 8 m, and
10. Luminaire distribution = type III medium semicutoff.

Figure 3 shows that the VI varies from positive to negative as the target is moved through the luminaire spacing cycle. The positive maximums occur just beyond the luminaires and the negative maximums occur with targets located just ahead of the luminaires. The value of the maximums decreases as the target goes farther down the roadway. This is due to the decrease in angular size of the target as the distance between observer and target increases.

To make sense of the comparisons with pavement luminance criteria, we need to establish methods of evaluating the merit of the visibility performance. Although it is not the intent of this paper to argue for or against a particular method, two arbitrary figures of merit for use in this study have been

Figure 4. Typical VI for visibility figure of merit.

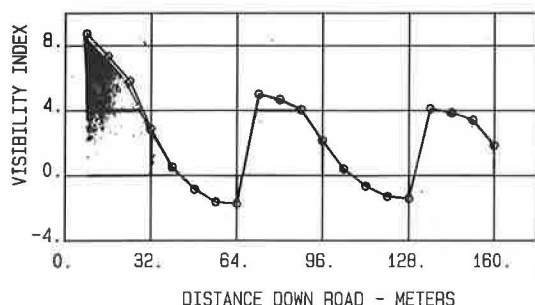
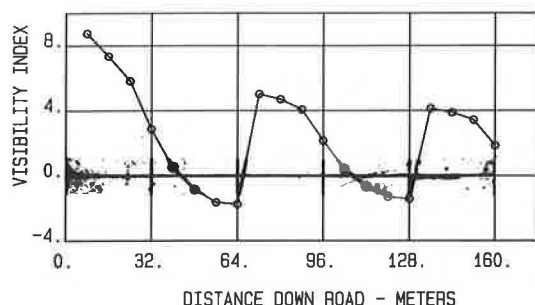


Figure 5. Visibility figures of merit for percent less than ABS one.



chosen. Figure 4 shows the one called VI Ave., which is the numerical average of the sum of the VI for each target position, disregarding the sign of the individual VI value. Figure 5 shows the figure of merit based on values that are less than absolute one. This is the percentage of the total number (20) of target positions that have a VI whose absolute value is less than one (referred to as $\%<1$).

Although we know that the observer's vehicle headlights will have a large effect on target visibility when within a few meters of the vehicle (up to about 60 m), we also know that the effect beyond approximately 60 m will be negligible. Unfortunately, the directional reflectance tables for the pavement do not have values for the angles that define the positional relation of the headlights to the pavement, so we cannot calculate the headlights' effect on pavement luminance. Therefore, all of this was done on the basis that the vehicle's headlights were off.

TARGET REFLECTANCE EFFECT

Figure 6 shows the results with target reflectances of 5, 20, and 40 percent. The table below shows that, as the theory indicates, the VI Ave. goes up and the $\%<1$ goes down as target reflectance goes up (note, Ave./min = average-to-minimum ratio):

Target Reflectance (%)	Visibility		Luminance	
	VI Ave.	$\%<1$	Lave	Ave./min
5	0.84	55	1.0	2.5
20	3.14	20	1.0	2.5
40	6.89	10	1.0	2.5

Observer and Target Location Effect

Figure 7 shows the results with the observer and target located in lanes 4, 5, and 6. The table below shows that, as the observer and/or target position is moved closer to being in line with the

Figure 6. VI versus target reflectance.

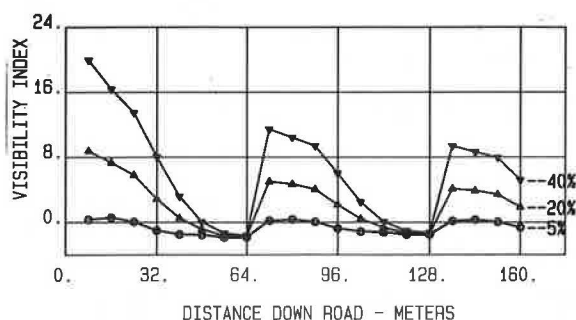


Figure 7. VI versus target position.

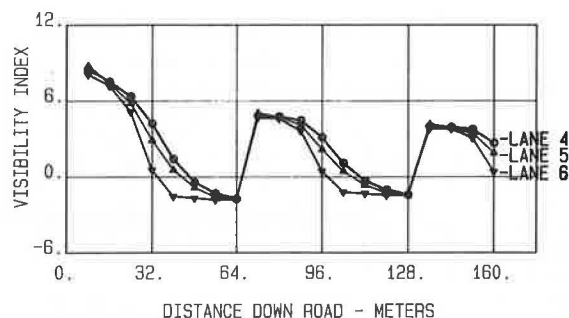
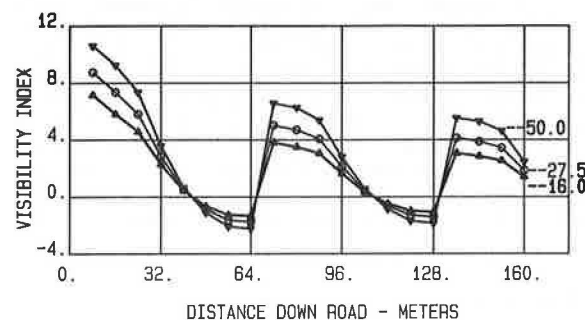


Figure 8. VI versus lumens.



luminaires on the right side of the roadway, the VI Ave. decreased but the $\%<1$ was not consistent:

Target Position	Visibility		Luminance	
	VI Ave.	$\%<1$	Lave	Ave./min
4	3.35	10	1.0	2.5
5	3.14	20	1.0	2.5
6	2.88	15	1.0	2.5

This needs some further study to determine the significance.

Lamp Lumens Effect

Figure 8 shows the results as the lamp lumen package is changed from 16 000 to 27 500 to 50 000 lumens. The table below shows that, just as theory would predict, the Lave increased in direct proportion to the lamp lumens:

Lamp Lumens (000s)	Visibility		Luminance	
	VI Ave.	$\%<1$	Lave	Ave./min
16.0	2.42	25	0.6	2.5
27.5	3.14	20	1.0	2.5
50.0	4.04	15	1.8	2.5

However, VI Ave., while it increased, did not increase as much as the percentage change in lumens, and the change in $\%<11$ was not in the same proportion as the lumen change.

Luminaire Spacing Effect

Figure 9 shows the results of increasing the spacing-to-mounting height ratio (MH) from 3 to 8 to 12. The table below gives the numerical changes in pavement luminance and VI figures of merit due to changing the spacing:

Luminaire Spacing (MH)	Visibility		Luminance	
	VI Ave.	$\%<11$	Lave	Ave./min
3	2.28	25	1.7	2.4
6	3.14	20	1.0	2.5
8	3.63	10	0.8	6.6
12	3.45	25	0.5	109

The change in the Lave and luminance uniformity are as expected. However, we see that the VI Ave. increases as the spacing is increased up to about 8 MH and then decreases as the spacing is increased further. The $\%<11$ values follow this same trend. Because this increase in VI Ave. up to 8-MH spacing is contrary to what we have traditionally assumed (we always thought visibility was directly correlated with average pavement luminance), some further analysis is warranted.

Figures 10 and 11 help to explain what is happening to the VI value at each individual target position as the spacing is increased from 3 to 6 MH. Target position 1, with a spacing of 3 MH, has a large contribution to background luminance from luminaires 3 and 4. The greatest contribution to target luminance comes from luminaire 2. When the spacing is increased to 6 MH, in effect you have eliminated luminaires 1 and 3. The loss in background luminance is greater than the loss in target luminance; therefore, the contrast has increased. Also, the veiling luminance has decreased due to the removal of luminaire 3, which results in the DGF increasing. The overall result is an increase in the

Figure 9. VI versus spacing.

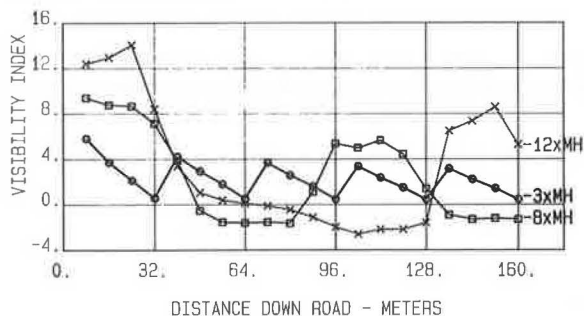
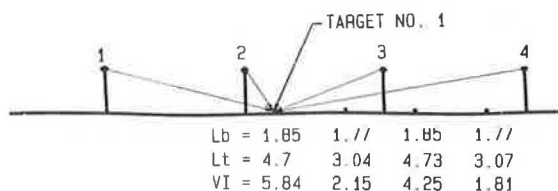


Figure 10. Three-MH spacing.

EFFECT on Lb, Lt, VI.



VI value for target position 1. Going through this same exercise for all target positions shows that the total sum of the absolute VI values increases, which results in the VI Ave. increasing.

Luminaire Mounting Height Effect

Figure 12 shows the result of increasing the luminaire mounting height from 7.9 to 10.7 to 13.7 m. The table below shows that the figures of merit for pavement luminance and VI move in the same direction with changing MH, but the VI Ave. changes at a faster rate:

Luminaire Mounting Height (m)	Visibility		Luminance	
	VI Ave.	$\%<11$	Lave	Ave./min
7.9	4.41	0	1.1	3.1
10.7	3.14	20	1.0	2.5
13.7	2.1	15	0.9	1.6

The pavement luminance ratio is $1.1/0.9 = 1.22$, while the VI Ave. ratio is $4.41/2.1 = 2.1$. This could be a significant factor in designing roadway lighting geometry for an optimum VI figure of merit.

Luminaire Distribution Effect

Figure 13 compares the VI difference between a luminaire with a II long-cutoff distribution to one with

Figure 11. Six-MH spacing.

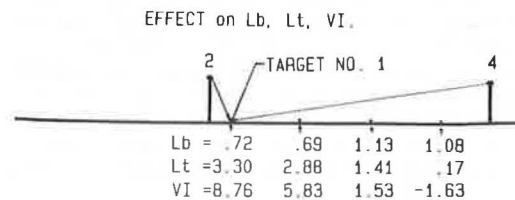


Figure 12. VI versus mounting height.

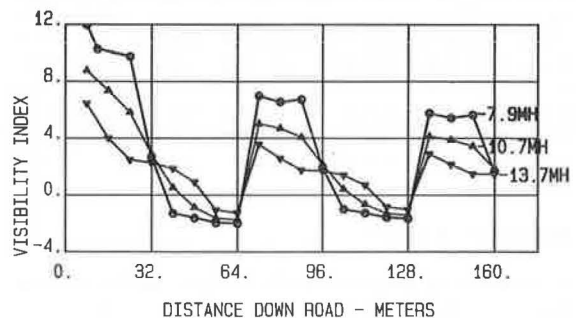
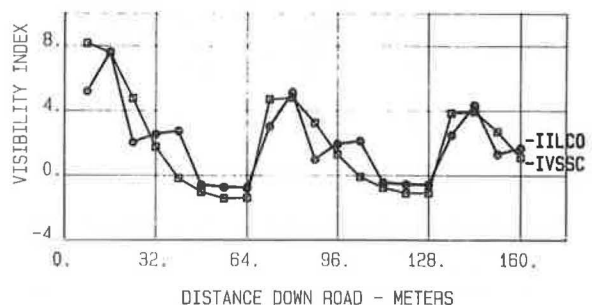


Figure 13. VI-luminaire distribution.



a IV short-semicutoff distribution. The table below gives the numerical results:

Luminaire Distribution	Visibility		Luminance	
	VI Ave.	%<11	Lave	Ave./min
IV short semicutoff	2.75	15	0.7	2.0
II long cutoff	2.37	30	1.2	4.0

As we would expect, the change in the pavement luminance figures of merit are significant. The change in VI Ave. was very small, but the change in %<11 was 2 to 1. This also warrants some further study.

Arrangement Effect

Figure 14 shows the results of changing the luminaire arrangement on the roadway from single-sided left to opposite to staggered. In this arrangement analysis, the roadway was changed to 13.4-m width with four 3.35-m-wide lanes. The observer and targets are located in lane 3 (numbered from the left side). Figure 14 shows the results with spacing of 64 m. The table below gives the numerical results that correspond to Figure 14:

Luminaire Arrangement	Visibility		Luminance	
	VI Ave.	%<11	Lave	Ave./min
Single left	3.1	25	0.95	7.6
Opposite	4.5	0	1.9	2.0
Staggered	1.7	25	1.9	2.0

The pavement luminance figures of merit, as expected, do not significantly change going from the opposite to the staggered arrangement but do significantly change when going to the single-sided arrangement.

However, the effect is just the opposite for the VI figures of merit. The change from opposite to single-sided VI Ave. decreased by 30 percent, but going to staggered the VI Ave. decreased by 60 percent.

In this study, the word correlation is not used in the sense of a rigorous statistical relation but is used to indicate that VI criteria consistently move in the same direction as luminance criteria. On this basis, when the physical parameters (i.e., spacing, mounting height, etc.) that are expected to effect both visibility and pavement luminance are varied, no correlation is found in four out of seven of the parameters. This is shown graphically in Figure 15.

FIELD STUDY

To check the correlation between the CIE 19/2 model and an actual roadway installation, the research and visibility subcommittee of RLC of IESNA conducted a field study on a roadway in Chicago in October 1982. (Although the committee report has not yet been made public, permission to use the results was given.)

The roadway was two 3.7-m lanes with 400-W mercury type III medium semicutoff luminaires mounted at 10.7 m and with 64-m spacing. Targets with the same physical dimensions as described above and of 5, 17, 20, and 30 percent reflectances were used. These targets were located at three different positions with two different observer positions.

Measurements of target luminance and background luminance were made with a Pritchard photometer by using the 6-minute aperture. The visual task evaluator (VTE) was used by an observer experienced in its use to get a measure of the \bar{C} . (Note, \bar{C} is a weighted measure of contrast by the VTE.)

Figure 14. Luminaire arrangement.

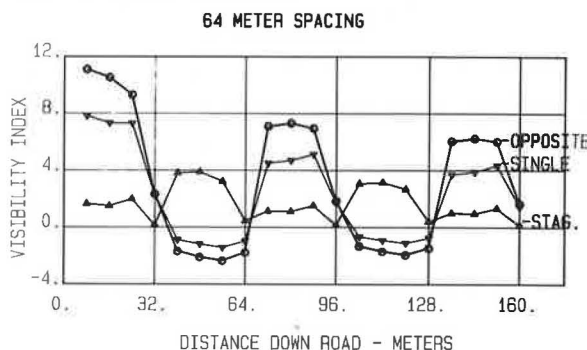


Figure 15. Correlation of luminance and VI.

	LUMINANCE		VISIBILITY INDEX		CORR?
	AVE	A/M	AVE	%<11	
TAR. REFL ↑	—	—	↑	↑	N.A.
TAR. LOC. ↑	—	—	↓	↓	N.A.
LUMENS ↑	↑	—	↑	↓	NO
SPACING ↑	↓	↑	↑	↓	NO
MT HT ↑	↓	↓	↓	↓	YES
PHOT DIST ↔	↑	↑	↓	↑	NO
ARRANG ↔	↑	↓	↓	↓	NO

Table 1. Field study, Chicago.

Test	Target		Results from Field Study			Computer-Predicted Results	
	No.	Percent	\bar{C}	VL	VI	VI	C^a
1	T1	5	-0.71	-1.73	-1.53	-0.89	-0.53
2	T1	17	-0.25	-0.61	-0.13	1.02	0.60
3	T1	30	T^b	—	—	3.10	1.83
9	T2	17	-0.56	-1.43	-2.44	-1.84	-0.97
14	T3	30	T^b	—	—	3.53	1.96

^a C is a measure of contrast from physical parameters.

^b T = threshold.

The measurements were used to calculate visibility level (VL) and VI as defined in CIE 19/2 and in the IES report (6, p. 40). Table 1 gives the VIs calculated from the VTE measurements as compared with the VIs predicted by the computer program that used the CIE 19/2 model. One observation is that the VI from both methods moved in the same direction: As the target reflectance was increased, the VI increased in the positive direction.

However, the VI from the VTE measurements never went positive, even though the contrast measurements from the Pritchard showed 30 percent of the targets to have positive contrast. It should be noted that the VTE indicated the same as visually perceived by several observers at the test site. Further to the point is that the computer runs that used the CIE model predicted that the VIs for both the 17 and 30 percent targets would be positive at target locations T1 and T3.

How can these differences be explained? The computer prediction program for the VI has been checked and, with the exception of the TAF, it does compute the VI based on the formulation from CIE 19/2. The

visual scene in the field study has a significant number of light sources in the field of view as well as periodically heavy traffic in both directions that seemed to be affecting target contrast and veiling luminance. None of these effects are accounted for in the computer-predicted VI. Do these factors influence our adaptation in a way that is not accounted for in the CIE 19/2 model?

These last questions indicate the need for further study to correlate field conditions with the measurement techniques and with prediction models. It is hoped that this additional study can be done within the next year.

CONCLUSIONS

Although further study is warranted to fine-tune the results of varying specific physical parameters related to pavement luminance and VI figures of merit, the study to date was rigorous enough to draw some basic conclusions. These are as follows:

1. Average pavement luminance is not a predictor of average visibility of the small target used based on the model of CIE 19/2,
2. Uniformity of pavement luminance is not a predictor of improved VI figures of merit based on the model of CIE 19/2 for this target, and
3. Many application techniques commonly used to improve the figures of merit for pavement luminance cause reductions in the figures of merit for VI based on CIE 19/2 for this target.

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Methodology for Determining Pavement Reflectivity for Roadway Luminance Calculation

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The field test procedures for determining the reflective properties and the macrostructure of a pavement surface are described. The light-reflecting characteristics of roadway surfaces affect the quantity and quality of light reflected (luminance) from the pavement. The luminance of the pavement surface and its uniformity affect the visibility of objects on the roadway surface. The uniformity of luminance patterns reduces confusion and clutter and stabilizes the driver's adaptation state. Improved visibility through better roadway lighting can result in increased safety for the nighttime driver. The luminance of the pavement is the product of the light arriving at a point (illumination) multiplied by the luminance factor. The luminance factor represents the directional reflectivity of the pavement, which is a function of light source location, observer location, and macrostructure or microstructure of the pavement. The parameters used for test-site selection and a matrix of test-site variables are presented. Once a test site has been selected, the test-site locations for reflectance measurements, British portable tester, and sand patch are defined, and the preparation and measurement techniques are described. As reported in the paper, problems were discovered in the reflectometer mechanism electronics that invalidated the test data. The methodology presented provides insight into the complexities of making pavement reflectance measurements. The procedures described lay the foundation for subsequent field measurements. The measurements are required to establish a simplified pavement reflectance classification system that is crucial to roadway luminance calculations.

Fixed roadway lighting is important to the nighttime driver. The safety of a driver at night is dependent on visibility, visual comfort, and driver alertness. These factors affect the driver's ability

to see objects on the roadway with sufficient warning to take appropriate and safe action. The visibility of an object on the roadway is dependent on the contrast between the object and its background (the pavement). The size and shape of the object, the state of driver adaptation, and the movement (versus stability) of the object also contribute to the visibility of the object.

Headlight penetration limits the driver's visibility to distances that are marginal for safe stopping. Vehicle stopping distance consists of reaction distance (reaction time \times velocity) and braking distance. The reaction time is directly related to object visibility. The object must be detected and recognized by the driver. The driver must respond to the recognition of the object and then initiate some form of action. The response to the recognition of the object and the initiation of action are related to the physiology of the individual driver. The detection and recognition are dependent on the visibility of the object. The size and shape of the object and whether the object is stationary or moving are beyond the control of the driver or the agency responsible for safety on the highway. However, fixed lighting systems can increase object contrast, driver adaptation state, and detection distance. The improved visibility can reduce reac-