discussed can be easily performed by following similar guidelines. A number of other cases and numerical examples are treated in Michalopoulos and Stephanopoulos (1).

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Abridgment

Discomfort Glare: A Review of Some Research

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Extensive research on discomfort glare as applied to roadways has been done in Europe by De Boer (1) and Hopkinson (2). However, discomfort glare research in the United States, as has most lighting research, has focused on interior applications. In the past few years, discomfort glare research conducted at Kansas State University under the sponsorship of the Illuminating Engineering Research Institute has been aimed primarily at fixed-roadway lighting. This paper surveys this research and briefly discusses its applications.

SINGLE-SOURCE STUDY

An initial major study was conducted with a single glare source.

Method

Putnam and others (3-5) did what might be considered pilot studies for this experiment by selecting the variables and the range of variation and by running a few subjects. The study summarized here is described in detail by Bennett (6).

Glare source size, position, and background luminance were independent variables; glare source luminance at the borderline between comfort and discomfort (BCD) was the dependent variable.

Glare source size was varied in five equal steps from 10^{-6} to 10^{-3} steradian. At arm's length, these vary from pinhole size to that of a quarter and were selected to cover the range of practicable sizes of the luminous parts of roadway luminaires. Source position varied in five equal steps from 0° (along the horizon) up to 30° above the line of sight (above the occluding angle of windshield tops). Background luminance was varied in five equal steps from 0.0034 cd/m^2 (0.001 footlambert) to 34 cd/m^2 (10 footlamberts). According to Kaufman (7), the former represents an overcast horizon night sky with the moon and the latter, an horizon sky on a very dark day.

Observers adjusted the luminance of a glare source to the BCD, which has been the common North American criterion for discomfort glare for about 30 years. The long instructions say that somewhere between a dim comfortable light and a bright uncomfortable one is a point of change or threshold called BCD. They further state that this threshold is neither the one that distinguishes pleasantness and comfort nor the one that distinguishes tolerable and intolerable. Rather, at BCD, if the glare source was made just slightly brighter, it would be uncomfortable.

The 97 paid participants in this study—primarily college students—adjusted (with replication) the incandescent glare source to BCD for 23 of the 125 possible combinations of the three variables in a confounded design. The observer looked at the pole of a 0.6-m (2-ft) radius hemisphere sitting on edge. By using a combination of a transformer and several neutral density filters (to reduce the voltage range and, hence, the lamp color variation), the glare source was set to BCD.

Multiple regression analysis, which involved some trial and error on transformations of variables, was performed. However, this work was largely guided by previously published research.

Results and Discussion

The selected multiple-regression model is as follows:

$$BCD = 200\,(L_B)^{0.3} \times e^{0.05A}/S^{0.6} \qquad (1)$$

where

BCD (in cd/m^2) = borderline between comfort and discomfort,
L_B (in cd/m^2) = luminance of the background ($r = 0.26$),
A (in degrees) = source angle above the line of sight ($r = 0.12$), and
S (in steradians) = source size ($r = -0.41$).

Comparisons of the results of this study to those of Putnam (3-5), Hopkinson (2), and others show essential similarities but with some differences in empirical constants. The BCDs in the Kansas State experiment tend to be higher than earlier results.

A later experiment with 24 new observers compared the source at 22.5° above the line of sight to one at 22.5° to the right of line of sight for the intermediate size and background luminance. No significant difference in BCD was found for these conditions.

Although the relative size of the correlations of the independent variables with BCD might be thought to indicate their relative importance, it is a function of the range of variation included in the experiment. Thus, originally there was an angle as large as 60°. This was eliminated because observers frequently could not achieve BCD at this high angle. However, to the extent that the ranges of variation are ecologically correct (i.e., they properly simulated the real world), the relative correlations are meaningful.

The coefficients of determination for the regression analysis show that more (0.54) of the predicted variation in BCD is associated with observers (individual differences) than the three independent variables (0.28). This is based on the inclusion in the multiple regression analysis of observers as dummy variables. That is, each observer was called "0" or "1" depending on whether he or she was currently in the equation or not (i.e., treated as a measure). The substantial coefficient of determination reflects the fact that there were large, consistent (over experimental conditions) individual differences in glare sensitivity or BCD. This may also be seen in the variation in the multiplier of the regression equation. This had a median of 217 (rounded to 200 in the equation), with a range from 0.52 to 8800—a ratio of almost 17 000:1. Wide individual variations in glare sensitivity have been long known to glare researchers and are discussed in the next section.

INDIVIDUAL DIFFERENCES

Although Fisher and Christie (8) found a relation between age and disability glare sensitivity, no other such finding and very little research on individual differences and discomfort glare have occurred. In 1972, 162 visitors during a Kansas State University open house made glare adjustments and filled out personal information forms. In 1974 and 1975, 199 open house visitors did the same. These were then interrelated. This work is described in more detail by Bennett (9).

Observers adjusted a 2.2×10^{-4} steradian (one degree) incandescent lamp at 0° with a 5.5-cd/m^2 (1.6 - footlambert) background luminance to BCD. Significant small correlations were found between BCD and age (-0.31), eye color (0.16), and indoor versus outdoor occupations (0.17). Older observers were more glare sensitive (had lower BCDs), and the empirical relation was found to be

$$\text{BCD, cd/m}^2 = 86\,000/\text{age, years} \tag{2}$$

Light-eyed observers and those with indoor occupations have lower BCDs (are more sensitive). The size of one's residential community, a person's sex or hair color, whether glasses are worn, type of occupation, and the sunniness of one's residential community were not significantly or consistently related to BCD.

The extreme conditions that produce disability glare almost always produce discomfort, but the more moderate conditions that may produce discomfort need not produce disability. Discomfort may be viewed as a warning reaction that could lead to the avoidance of disability-producing conditions or worse. Similarly, although discomfort and disability apparently have different physiological mechanisms, it makes sense for older people who are more sensitive to disability to be more sensitive to discomfort effects. People with more melanin have darker eyes, and the melanin filters out light so that they are less sensitive to glare.

Lane (10) found that people who have recently done more detailed close work (are visually fatigued) are more sensitive to discomfort. Thus, one might expect indoor workers to be more sensitive also.

All in all, despite a few significant correlations, this research has been rather unsuccessful in accounting for differences in sensitivity to glare in terms of demographic variables. Consequently, M. M. Babiker in a 1977 master's thesis done at Kansas State University studied personality and attitude variables.

A Personal Enlightment Test, given after preliminary screening, was developed that consisted of 64 personality, attitude, and demographic items. This test had items such as, "I am in just as good physical health as most of my friends" (true or false) and, "In your opinion, can headlight glare be prevented" (yes or no). This test was given in 1977 to 101 open house visitors. The visitors adjusted to BCD in the hemisphere with a 1.76×10^{-4} steradian source at 0° with a 34-cd/m^2 (10-footlambert) background luminance. In addition, the observers made similar white-noise adjustments to the borderline between comfort and annoyance (BCA).

Stepwise regression analysis to predict BCD resulted in a 22-item questionnaire with an R of 0.81. The total sample was arbitrarily subdivided into halves. A new nine-item question set based on stepwise regression of one-half of the observers predicted the other set of data with an R of only 0.21 (nonsignificant at 0.05).

Thus, again, the attempt to predict who will be sensitive to glare has proven elusive. It seemed plausible that personality items (largely anxiety items) and glare attitude items would be useful. Ostberg and others (11) did find a significant correlation (0.53) between a test of neuroticism and glare sensitivity. Also, the correlation between BCD and BCA was a nonsignificant 0.19, thus discouraging the idea of general personal sensitivity to environmental stimuli.

APPLICATION TO ROADWAYS

In one sense, the Roadway Lighting Committee of the Illuminating Engineering Society is the customer for the ongoing research. The Standard Practice produced by this committee has not included discomfort glare in its considerations. Although European standards do consider discomfort glare, U.S. and Canadian engineers have encountered difficulties in tests of these procedures. Consequently, North American research is under way.

The single-source experiment gives some results that should be applicable to roadway lighting. In some cases, however, such as at interchanges, vast arrays of many light sources appear in the field of view. For a line of lights along the driver's roadway, two counteracting effects take place. The near lights are larger but higher above the line of sight. The far lights are smaller but closer to the line of sight. Research is

Table 1. Estimated BCDs for roadway lighting for a single source.

		BCD (cd/m^2 000s)					
		Mounting Height at 3-m Lateral Distance (m)			Mounting Height at 9.1-m Lateral Distance (m)		
Longitudinal Distance (m)	Background Luminance (cd/m^2)	9.1	11	12	9.1	11	12
27	0.0034	11	14				
	0.034	23	25				
	0.34	45	51				
	3.4	89	100				
	34	180	200				
55	0.0034	17	17	21	21	21	24
	0.034	34	38	38	41	45	45
	0.34	69	72	79	82	86	93
	3.4	137	140	160	160	170	180
	34	270	290	310	330	340	380
82	0.0034	24	24	27	27	27	31
	0.034	48	51	51	55	55	58
	0.34	96	99	110	110	110	120
	3.4	190	200	210	220	220	230
	34	380	400	410	450	450	480

Notes: 1 m = 3.3 ft; 1 cd/m^2 = 0.292 footlambert.
Empty cells indicate < 20° cutoff to the top of the windshield.

under way to study such multiple-source effects.

In the meantime, Merle Keck of Westinghouse and Ramkumar Viswanathan of Kansas State each did analyses that related some representative roadway-lighting conditions to those involving a single light source. Table 1 shows BCDs estimated from an analysis based on the regression equation from the single-source experiment.

It was assumed that a varying visible portion of a 0.13-m^2 (200-in^2) cobrahead luminaire was mounted at 9.1 m (30 ft), 11 m (35 ft), or 12 m (40 ft). The driver's line of sight was assumed to be 1.2 m (4 ft) above the ground. The lights were assumed to be either 3 m (10 ft) or 9.1 m (30 ft) to the side of the driver's track. The BCD was examined at 27 m (90 ft), 55 m (180 ft), and 82 m (270 ft) longitudinally from the light.

In some cases, the light at closer distances was above the occluding windshield top. The BCDs may be appraised by observing that Viswanathan and I made a few luminance measurements of roadway lights in our neighborhood that ranged from 21 000 cd/m^2 (6000 footlamberts) to 86 000 cd/m^2 (25 000 footlamberts) (for mercury, high- and low-pressure sodium). If such an actual source luminance was viewed in a position where a lower BCD luminance was expected, one might expect at least half the observers to be uncomfortable. Thus, some analyzed conditions will be problems, some will not. Generally, most discomfort problems can be avoided by raising the mounting height. Other analysis is under way to figure out how to cope with skewed distributions of observers within conditions so as to specify various percentages of observers who would be discomforted.

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Economic Models for Highway and Street Illumination Designs

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A key issue in the field of illumination is energy conservation. At the same time, the application of economic resources should be optimized. For instance, to save energy, roadway illumination lamps can be replaced by more efficient lamps that provide the same light for less wattage. However, such energy savings may be offset by other cost elements. For these reasons, detailed cost calculations are needed to ensure lighting investment optimization. The cost-effectiveness of lighting systems can be established by the discounted total cost or annual equivalent cost models described in this report. These economic models allow various cost items, such as capital outlay, maintenance, and operational and en-