Characterizing Discomfort Glare from Roadway Lighting

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The Kansas State University discomfort glare research program, which began in 1970, has supported research on discomfort glare from roadway lighting. Early experiments on static, single sources that made use of the North American discomfort glare criterion and the subjective judgments of observers required special multiple probit analysis to render the results reproducible. The data consisted of determinations of the borderline between comfort and discomfort (BCD) as functions of observer and source characteristics. Personal qualities such as age, sex, and eye color were correlated with glare. Source characteristics included duration of exposure, distance, size, number, and spacing. Further studies were made concerning the stability of observer responses with the passage of time, both for short and long time intervals. More recently, a dynamic simulator has been constructed in which the observer is placed in the driver's seat of a part of a car body, and four lighting systems are alternately used to simulate real-world glare conditions.

Research supported by the Illuminating Engineering Research Institute and the state of Kansas on discomfort glare related to interior lighting was carried out beginning in 1970. During this effort, the Illuminating Engineering Society of North America Roadway Lighting Committee decided to consider discomfort glare from fixed roadway lights. Glaremark, the European predictive system, was tested on a street in Philadelphia. Not much relation was found between how observers reported discomfort there and the predictions of Glaremark.

An inherent difficulty for Glaremark (or any predictive system) in predicting the results of actual roadway lighting is that the actual roadway lighting systems tend to be reasonable from the standpoint of discomfort, and thus the small differences between systems are hard to predict.

In any case, the committee decided it needed to develop its own North American system that would be more effective. As a result, the Kansas State University (KSU) discomfort glare research program was redirected to support this roadway effort.

The paper *Discomfort Glare: Parametric Study of Angularly Small Sources (1)* was a report of the first roadway discomfort research carried out at KSU. Some years earlier, Putnam and his students had published three papers in *Illuminating Engineering* from the master's theses of the students *(2–4)*. In a sense, these were pilot studies on roadway discomfort—they were pioneering and used few subjects.

An experiment was designed on the basis of this earlier work. A total of 97 observers looked at a glare source mounted at the pole of a hemisphere set on edge. Using a transformer, they adjusted the luminance of the glare source to the borderline between comfort and discomfort (BCD). This process is the commonly used North American discomfort glare criterion or response. A range of source angular sizes, source positions, and background luminances was selected to cover actual ranges of these conditions that might be encountered on roadways. For each of these parameters, five levels were established to cover the range. Because a complete factorial design of $5 \times 5 \times 5 = 125$ conditions would have been unwieldy, a deliberately confounded experimental design of a selected 23 conditions was used. The maximum glare source luminance of the order of 1 million foot-Lamberts (fL) (a 1,000-W incandescent projector lamp) was used to enable the observers to adjust the glare source to BCD under most conditions. Even so, there were tens of cases of missing data where the observers could not make the light bright enough to reach the BCD. The study was a single-source, static simulation.

It is common in research with subjective judgments to find wide individual variations and differences among the responses. This effect, of course, had been noticed by discomfort glare researchers before. The lack of a statistical tradition in illuminating engineering in general and among glare researchers in particular meant that the standard variations had not been quantified and were thought of as error. Statistical analysis was invented to cope with such variations. The analysis of data in the 1977 study *(1)* showed that the percentage of variance associated with differences among people was substantially greater than that associated with the experimental variables of size, position, and background.

Two reports *(5, 6)* were what may be called collateral reports—studies the motivation for which arose out of the discomfort glare program. In Babiker's thesis *(5)*, personality characteristics of people who were particularly sensitive to discomfort from glare or noise were sought (unsuccessfully). As it turned out, there was no relation between being sensitive to noise and being sensitive to glare, and personality factors also failed to correlate. The other research *(6)* was a study of hundreds of people who went through the author's open house. Various personal qualities such as age, sex, and eye color were correlated with sensitivity to glare. Although there were some small, statistically significant correlations, such as a negative 0.19 with age, there was no correlation of any particular size. The age correlation means that older people are slightly more sensitive to glare than younger people. People of ages from about 8 to 80 were tested.

In the study by Ahmed and Bennett *(7)*, when the duration of the exposure of the glare source was varied from 0.01 to 10 sec, a complex relationship was found. Some sharp changes took place in the very short range. Possibly these exposures were so brief that observers had difficulty making judgments, but probably some other matters of visual functioning happened. For

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the longer-duration exposures, BCDs increased, probably indicating the effects of adaptation.

Rubison *(8)* reanalyzed the 1977 data using multiple probit analysis, a statistical technique that enables the mathematical prediction of any arbitrary percentage in a distribution in a multidimensional space. In the 1977 report *(1)*, a multiple regression equation predicting the mean BCD response was fitted as a function of the size, position, and background of the source. The multiple probit does the same thing except that instead of predicting the mean it predicts the whole distribution, so that the variation of observers about the multiple regression surface no longer looks like error variance but is the basis for the distribution of responses. So the error has been converted into something predictable and thus statistically controllable.

In the summer of 1980, the 1977 experiment was rerun with various methodological improvements. Remarkably similar regression analysis exponents resulted, showing the reproducibility of discomfort glare results despite large individual differences.

The studies by Bennett *(9–11)* were continuations of the main research program. Several experiments were carried out extending the static, single-source simulation to a static, multiple-source simulation. The number of sources and the relative size and spacing of several sources along the roadway were examined. (In real life, a string of lights is seen in perspective—the lights become smaller and closer together as one looks further down the roadway.) These experiments showed that size, spacing, and number did make a difference and, most important, that while having more lights created greater discomfort, the first, largest light was by far the most important. Analysis with the cumulative brightness evaluation (CBE) predictive system showed that the contribution of the second light might be of the order of 1 percent of the first light. Subsequent lights are even more trivial. This last result agreed closely with results of Adrian in some of his unpublished work.

The first study *(12)* is a report of the important research that showed range effects. That is, when the range (upper value) of glare source luminance was increased by 10 times (30,000 to 300,000 fL), the BCD increased by 7 times. This increase was the principal motivation for the 1980 repetition of the 1977 study. Instead of the 1977 upper value of glare luminance of almost 1 million fL, the maximum luminance was restricted to a value closer to that which might be seen on roadways. Indeed, the newer results showed a substantial lowering of the coefficient of elevation of the regression formula as expected. The second report *(13)* was a different approach to cope with range effects. A single-glare source was shown to hundreds of observers who simply reported whether it was above or below BCD, and then the 50 percent BCD was determined. The value in this case was about 5,000 fL for rather moderate conditions of size, and so forth. Because no range of luminance was involved, there could be no range effect; hence this result is an unbiased assessment. Unfortunately, it could be expensive to run hundreds of subjects for each experimental condition.

The range effect finding disturbed a number of people who were accustomed to thinking of the mechanism of discomfort glare as a simple physiological mechanism such as the pupillary response suggested by Fry and his students *(14)*. Whatever physiological mechanisms may be involved in discomfort glare, the range effect simply shows that there are also important psychological (central nervous system) bases.

Bennett *(15)* tells about two types of effects from several studies. The research has always used the borderline between comfort and discomfort (BCD) as the observer's response. As a verbal effort to reduce range effects, several other responses (such as "uncomfortable") were defined and obtained to anchor (make more stable and lower) the observer's responses. One experiment showed that, indeed, this did happen. BCDs were substantially lower with these anchors than without them.

As a logical extension of the previous work and used in more recent research is what was called the new North American glare scale. Basically, this was the 9-point deBoer scale with both his and our verbal labels as anchors. The numeric direction has been reversed from deBoer to be more consistent with North American practice. (People were asked to judge degrees of discomfort, not degrees of comfort.)

The other part of this research concerned what was called the stability of the observer's glare responses. Several years ago, using the BCD response cited previously, glare responses were made twice a week throughout a semester. Then, after a few years, using the different students who were now present, the original study was repeated, except that multiple criteria were used. These anchoring criteria did not overcome the time effects. Basically, some observers kept a constant response criterion—gave the same types of responses over the semester. Others gave higher and higher BCDs over time; their values were definitely not stable. Although this study had an insufficient number of subjects (it was done cost-free), it refuted published reports by Hopkinson (using only two subjects) that observers became less sensitive to glare with experience.

Some critics interpret this result as a refutation of the entire research program on discomfort glare. Instead, the situation is typical of applied research, and in a sense all applied research is simulation. This phrase means that for those conditions that make a difference (such as maximum luminance of the glare source, because there are range effects), the actual conditions of the application must be simulated. Thus, for this aspect, for studies of discomfort glare from roadway lighting, subjects ideally would approximate the experience of drivers in general. Further, because most drivers have not ever been asked to explicitly give their discomfort glare reactions, experience of this sort is unnecessary or even undesirable in subjects.

The reports by Anantha et al. *(16)* and Bennett *(17)* constituted the first reports on research in which interest moved from a static, multiple-source simulation of the roadway to a dynamic, multiple-source simulation. [Anantha et al. *(16)* emphasized the simulation, Bennett *(17)* the experimentation.] The simulation approach was based on an idea of Fry's *(16)* in which a rotating spiral turned behind a narrow sector. Where they intersected at several places simultaneously, a series of lights would be seen in perspective. By computing the particular spiral and sector, a particular set of lighting conditions could be seen.

The results, which contrasted 0, 30, and 60 mph, showed that as speed increased, so did the discomfort, thus justifying the need for a dynamic simulator. This finding was confirmed in the next year's research. Spacing was found to have a significant but reversed (to expectation) effect, but this was due to the limits of the simulation. In this dynamic simulation, both the number of lights and whether they were placed on one or both sides of the road had effects. One interesting result concerned duration of glare exposure and fatigue. The study was conducted so that exposure to glare on response could be compared in several steps from 0 to 3 hr. No time effect was found, consistent with other results on visual fatigue.

Research by Bennett et al. *(18)* was a potpourri of attempts to understand and control the discomfort reaction psychologically. Some good indications of the possibility of psychological control were found.

The reports by Easwer et al. *(19)* and by Bennett *(20)* dealt with an improved dynamic simulator. A written report on the research results has not yet been published. Because a number of aspects of the first version of the dynamic simulator were unsatisfactory, a better one was designed and built. The observer was placed in the driver's seat of a part of a car body, the optics were unfolded from the disks to the observer, and new disk mechanisms, larger disks, light sources, and cooling were built. In particular, the larger disks created problems.

Some 60 observers drove the simulator with four alternative lighting systems—post-top, cobrahead, high-pressure sodium cut-off, and high-pressure sodium long cut-off. Both Glaremark and the CBE predictions were then related to the results. Analysis using the two predictive systems showed, as did the second Philadelphia study by Keck and Odle *(21)* that the predictions did not agree with each other or with the observers' responses.

Some 60 observers also drove through six roadway lighting systems in Manhattan, Kansas, and using the Fry dynamic simulator encountered simulations of the same six systems. After each system, they made discomfort glare judgments. The results showed close rank-order correlation between real-world and simulation results and the CBE predictive system. No agreement was found for any of these with the Glaremark predictions *(22)*.

An experiment to determine the effects of nonhomogeneous background luminance on discomfort glare was performed with 40 student subjects *(23)*. To simulate the real-world roadway conditions, the background luminance was divided into three zones of illumination, namely, the sky, the pavement, and the side luminance zones. Combinations of three specific luminance levels were chosen for each of the background zones based on an initial survey of Manhattan, Kansas, streets and on measured background luminances. A flat reflector simulated the nonhomogeneous background luminance conditions of the real world. The subjects evaluated the glare based on the BCD criterion. In general, within the ranges studied background luminance in the various areas had no impact on discomfort.

Currently, research is being completed on the effect of varying intensity of the lights along the roadway. Varying intensity appears to have little impact on the degree of discomfort.

ACKNOWLEDGMENT

TRB staff would like to acknowledge that answers to editorial queries were promptly provided by S. Konz, Department of Industrial Engineering, Kansas State University.

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