MOTOR VEHICLE HEADLIGHTING – A CLASSIC PROBLEM IN ERGONOMICS

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Introduction

Years ago, fresh out of school, I became interested in the problems of motor vehicle lighting in general, and headlighting in particular. It seemed to me that this was an area clearly amenable to the scientific method. Surely some effort by someone like myself could yield workable solutions and genuine improvements in a reasonable time frame.

I have been fortunate enough to have had considerable support over the years so that I could carry out much work in this area. As I look back on this experience it is with a certain amount of embarrassment at my naivete of some years ago. Like many other problem areas, headlighting only looks simple to those who know relatively little about it. Despite my best efforts, and those of a number of other very capable persons, many of the same problems remain, and “the optimum beam pattern” remains an elusive concept.

The reasons why there is so much difficulty can be summed up briefly by pointing out that there are a great number of criteria to be considered in headlight design, many of which are in conflict. Unfortunately, there is no agreement as to how to weight criteria that are in conflict. For example, almost anything that can be done to improve visibility down the road will increase glare to some degree, under at least some conditions. In order to decide whether the increase in visibility represents a system improvement, it is necessary to determine whether that benefit outweighs the negative aspects of increased glare. The problems in making such a decision are compounded by the fact that there is generally no way to quantify the glare effect or determine how often or under what conditions it will occur. Progress toward a solution of this dilemma has been made in recent years through the creation of a computer model that affords a comprehensive evaluation of headlamp beam patterns (Bhise, et al., 1977), of which more will be said later.

Working on problems of vehicle headlighting is interesting because there are a great number of fascinating research topics to be pursued. But, in addition, there are fundamental criterion issues that require negotiation and agreement among interested parties. The engineers have been busy as well, and new technology is forever adding to the list of things to be considered. It is, in short, like many other areas in which Ergonomics is involved.

What I would like to do in this paper is briefly cover some of the areas of major concern, discuss the conflicts, review the data, and suggest how a solution might be arrived at.

Illumination

The purpose of headlamps is obvious; they are to illuminate the area ahead of the vehicle so the driver can acquire necessary visual information. The very obviousness of their purpose is a problem in itself. For example, many people seem to believe that if we want to see "better" it is only necessary to increase the output of the lamps. Surely, they reason, a means can be found to keep that illumination out of the eyes of other drivers.

First, it is necessary to understand that the relationship between visibility distance and lamp output is nonlinear. This is illustrated in Figure 1, taken from Roper and Howard (1938). This figure shows that, once one has reached levels of illumination such as those provided by modern headlamps, additional visibility distance can be obtained only through very large increases in output. Not only would such increases create technical problems in lamp and electrical system design, but they would also complicate the problem of glare control.

Contrary to what some people seem to think, there is no means to ensure that headlamp illumination will not reach the eyes of other drivers. There are two basic reasons. First, there are a host of practical problems. For example, roads have horizontal and vertical curvature, so that illumination intended for the road surface will sometimes be projected into the eyes of another driver. In addition, headlights are attached to the sprung mass of the vehicle and point up or down depending on the vehicle's pitch angle. And, an important limitation is the fact that automobiles are owned by individuals, many of whom have little technical knowledge, and/or do not maintain their vehicles as well as would be desirable.

The other reason why glare cannot be kept out of the eyes of other drivers is that it is actually necessary to project some illumination into the areas of the forward field in which their eyes are located. It is this "necessary" glare that has been the impetus for a great deal of the really interesting work in headlighting. Much of the rest of this paper will be devoted to a discussion of this work.

Figure 1.. Visibility distance as a function of beam candlepower and target reflectivity (50).
 (Candlepower values are X 1,000.)
 (Visibility distances are X 10 feet.)

The Measurement and Assessment of Glare

Glare from headlamps is unquestionably the major area of disagreement among various researchers in vehicle lighting. The problem is that glare is an entirely negative phenomenon. Hence, it is natural to adopt an attitude of "the less glare the better." But, as pointed out earlier, glare is also inescapable. That being the case, the challenge to the designer is not necessarily to minimize exposure to glare, but to minimize exposure to glare levels that are disabling or excessively uncomfortable. This notion requires that the effects of glare be quantified.

When considering the effect of glare on the ability of the driver to see (commonly called disability glare), there is a great deal of information available. As it happens, the loss of visibility associated with glare is relatively easily measured, and accurate models of the process have been developed.

Glare also affects the driver's sensation of comfort (commonly called discomfort or psychological glare). Here the problems of measurement are much different. Because discomfort is a subjective sensation, it must be assessed using techniques such as rating scales. The results are affected by the type of scale as well as the test methodology, and there can be problems in interpreting the test results. Perhaps because of these problems there has been less work reported on discomfort glare, and agreement on an appropriate model is lacking.

In the context of automotive lighting, most investigators have made use of a rating scale first described by deBoer (1973). This is a 9-point scale, as follows:

- 1 Unbearable
- 2
- 3 Disturbing
- 4
- 5 Just acceptable
- 6
- 7 Satisfactory
- 8
- 9 Just noticeable

Among the studies that have made use of this scale, the most significant is probably that of Schmidt-Clausen and Bindels (1974). These investigators looked at glare angle, adaptation level, and glare intensity as independent variables in a laboratory study. Subjects were given brief (2-second) exposures to fixed levels of glare and provided a rating of each using the deBoer scale. The results, for one combination of variables, are given in Figure 2. Based on these data, the peak glaring intensity of low-beam headlamps of the type currently in use in the United States in a meeting on a straight, flat, two-lane road would be rated about "4," suggesting that these units are already providing excessive discomfort, and that further increases in output are undesirable.

Schmidt-Clausen and Bindels developed a mathematical model of discomfort glare. One version of this model (as described in Bhise et al. [1977]) is as follows:

$$W = 2 \log_{10} (1 + 269.0966 L_a) \\ - 2 \log_{10} (\sum E_i / \theta_i^{0.46} - 2.1097)$$

Where W = value on the deBoer scale

L_a = adaptation luminance

E_i = illumination directed toward the observer's eyes from the i th source

θ_i = glare angle

If there is a cause for concern with the Schmidt-Clausen and Bindels work, it is in the fact that the method they employed is a poor simulation of the way glare is experienced in real-world meetings with other vehicles. Prior to incorporating the Schmidt-Clausen and Bindels model into their comprehensive headlamp evaluation model (CHESS), Bhise et al. (1977) carried out an evaluation using dimming requests as a criterion. This study was run on public roads in such a way that the investigators could calculate glare at the eyes of oncoming drivers and measure the distance at which they flashed their headlamps to request dimming. They found that dimming requests began increasing rapidly when the glare experienced was such as to produce a rating of "4" or less.

Measuring dimming requests in real-world driving situations seems like a very reasonable approach to measuring the discomfort produced by headlighting systems. Unfortunately, there is a problem. As we noted earlier, glare is an entirely negative phenomenon, and the concern is that people will respond when they think they are being

Figure 2. DeBoer ratings (W) as a function of glare illuminance. (From Schmidt-Clausen and Bindels, 1974.)

glared more than necessary (i.e., that the test car is on high beam), as opposed to when they are experiencing discomfort. Some indication that this may be the case can be found in instances in which four lamps on a test car received more dimming requests than two lamps, even though the glare was the same (e.g., Mortimer and Olson, 1974). If, indeed, drivers are merely responding to what they believe to be high beams, then dimming requests are probably based on present lighting practices, and do not necessarily tell us very much about actual discomfort.

In our most recent study of low-beam photometrics (Olson and Sivak, 1983), we carried out two significant investigations concerning discomfort glare. One of these was a laboratory study that sought to replicate the Schmidt-Clausen and Bindels' work. The results were identical, suggesting at least that Americans and Europeans perceive glare in the same way. The second study was run full-scale, using cars in actual meeting situations. Subjects were seated in one vehicle and observed a glare vehicle approaching for a distance of about 0.5 km, rating the glare provided by its headlamps after it passed. The results of this second test are shown in Figure 3, compared with predictions based on the Schmidt-Clausen and Bindels' equation. The differences are substantial. For example, a glare level that would be rated "4" based on the equation, would be rated 5.5 - 6.0, based on the results of the field test. These results reinforce the suspicion that laboratory methods such as those described may not yield results that accurately reflect real-world responses.

Recently Sivak and Olson (1987) reported the results of an effort to develop a simple, reliable field glare evaluation methodology. The procedure was based on responses to a questionnaire sent to a number of leading researchers in vehicle lighting. In this test subjects either drove or rode in one vehicle and rated the glare provided by the lamps of another (stationary) vehicle. Ratings were taken at two separation distances. Interestingly, although different methodologies were used, the results of the two field studies just described compare reasonably well.

A concern of ours has been the interpretation of data obtained using the deBoer scale. For example, scale point "5" is labeled "Just acceptable," implying that anything more intense than that would not be acceptable. Since the upper limit of discomfort glare is a critical point, it is important to define it with as much precision as possible. To "calibrate" the scale we ran two studies. In one the subjects rated a number of glare levels using the deBoer scale. On another occasion the same subjects rated the same glare levels, this time using a 3-point scale. The scale employed descriptions that made intuitive

Figure 3. Mean ratings assigned each glare condition compared with prediction based on use of DeBoer equation.

sense to us. Specifically, the subjects were instructed to rate the glare A, B, or C according to the following criteria:

A The glare produces no sensation of discomfort at all

C The glare is so intense that the subject would like to make some avoidance response, such as closing the eyes or holding up a hand to block it out.

B Any glare exposure that could not be rated A or C.

The results of this study are shown in Figure 4. The distributions of A and C ratings cross over at a level very close to that the subjects rated "5" using the deBoer scale. Ratings of C occur about 20% of the time at a deBoer rating of "4," but climb very rapidly as glare levels are increased above that point. This suggests that an appropriate upper limit for discomfort glare would be a level that elicits a mean rating of "4" using the deBoer scale.

The assessment of discomfort glare by means of rating scales is made somewhat more difficult because of the "range effect." The range effect had been noted some time ago in the assessment of other noxious stimuli, but was first applied to glare by Lulla and Bennett (1981). What was found was that the rating assigned to any particular stimulus depended on the range of stimuli supplied. In other words, the ratings were to some degree relative, instead of absolute.

We were interested in determining if the range effect applied to ratings of headlamp glare made using the deBoer scale. Two studies were run, one in the laboratory, and one in the field. In each case the subjects made ratings of glare discomfort, using the deBoer scale, under two conditions, i.e., "full" and "truncated" range. The truncated range was arrived at by eliminating several glare levels from one end of the continuum presented to the subjects. The results of the laboratory study are presented in Figure 5. In this case the truncated range was achieved by eliminating the four highest levels of glare. Note that the ratings assigned the lowest levels of glare were the same under both conditions. However, the ratings diverge at higher levels. The most intense levels of glare presented in the truncated condition were rated about one scale unit more uncomfortable than they were in the full range condition.

The range effect is a limitation on test methodology, true enough. But in all likelihood it also applies to the real world. If, through clever design or some other means, the glare exposure of drivers is changed, the implication is that their perception of glare discomfort will change as well. For example, suppose we could significantly reduce exposure to high levels of glare. The range effect suggests that perceived discomfort would

Figure 4. Percent of time various glare levels were rated "A" (no discomfort) or "C" (intolerable).

Figure 5. Mean DeBoer ratings assigned by subjects under two range conditions.

not be reduced as much as experimental data might indicate. These findings should give us pause when discussing discomfort glare and the need for designs that reduce glare levels, since such designs may alter the range of glare exposure. It is necessary to weigh the costs of such improvements against the actual gain in perceived comfort, not gains calculated based on the previous range.

The Older Driver

The term "older driver" is used rather loosely, and frequently seems to refer to individuals significantly older than the speaker or writer. For purposes of this paper "older drivers" will mean those drivers 55–60 years of age and older.

The concern about the older driver comes from two sources. One is accident statistics. Figure 6 (from Carsten, 1981) shows fatality rates as a function of age, corrected for mileage exposure. These data indicate that young persons, particularly males, have a very high rate. The rate declines rapidly after 20 years of age, reaching a plateau until about age 55, then begins to climb again. The interesting part is that the rate for male 70-year-old drivers is about the same as for 20 year olds. There are many possible reasons for these results, but among them are known, age-related changes in skills thought important in driving. These changes are the second source of concern about the older driver.

Certain age-related changes in vision are of consequence in the design of vehicle lighting systems. Two of these are illustrated in Figure 7 (from Olson and Sivak, 1981). This was a laboratory study of the effects of glare on the ability to detect low-contrast targets. The vertical axis of the figure indicates the luminance of the target at threshold. To start the test, a glare source, equivalent to high beams at about 30 meters, was switched on. The subjects adjusted the luminance of the target to keep it just visible. Note that the older subjects were more affected by glare initially, and it took them about 50% longer to reach a stable level, which required about double the target luminance of the younger subjects. Other measures taken in another portion of the same series of tests indicated that, compared to young subjects, older subjects required the target to have about twice the luminance at threshold under no-glare conditions.

In the United States the percentage of older persons is rising rapidly, and will continue to rise for some time in the future. In general, these people are better off physically and financially than ever before. This means they will want to retain as much mobility as possible for as long as possible. Clearly, their vision characteristics present a special challenge to the designer of lighting equipment.

Figure 6. Fatality rates per 100 million passenger miles by age of occupants of cars, vans and light trucks in 1977-78 (from Carsten, 1981).

Figure 7. Luminance required on target disc to provide threshold visibility as a function of time after onset of 75.3 lx glare.

The Visibility of Retroreflective Signs

Illumination projected above horizontal from headlamps is sometimes called “glare illumination.” In one sense this is an unfair characterization, because it implies that such illumination is unwanted or “bad.” In fact, as noted earlier, illumination projected above horizontal is useful, even necessary. One of the most important reasons is the necessity of detecting and reading reflectorized highway signs.

Signs must capture the attention of an approaching driver, and convey a message. All of this must be accomplished while leaving the driver sufficient time to take whatever actions are called for. Since retroreflective signs lose their reflectivity over time, a major question facing traffic agencies is determining the point at which signs should be replaced in order to ensure that they will continue to function adequately. This turns out to be a very difficult question to answer. However, recent work by Mace et al. (1985), Morales (1987), and Olson (1988) has begun to provide some guidelines. For example, Table 1 reproduces Olson’s recommendations for minimum SIA’s (sign intensity per unit area), in cd/lux/m^2 , for an overhead guide sign (white letters on a green background) in a dark, rural setting. One of the assumptions made in the preparation of these recommendations is that the headlamps of approaching cars have certain photometric characteristics. If the “glare illumination” in motor vehicle headlamps is reduced significantly, then more efficient (and more expensive) retroreflective materials, or special illumination, will be required to provide the necessary sign brightness. It may also be necessary to replace signs more often and erect additional signs in some areas.

Conclusions

Given the great number of conflicting requirements for headlamps, how can we hope to begin to move toward a “best possible” design? Clearly, it is necessary to consider combined effects, something that has rarely been done to date. One example of the kinds of comparisons that are necessary is found in data provided by Yerrell (1971). Yerrell took measures of the glaring and illuminating intensities of headlamps on passing vehicles at four sites in Great Britain and another four sites on the Continent. Figure 8 shows the cumulative frequency distributions of the glare intensities. Because the European headlamp is designed to provide low glare levels under ordinary meeting situations, the results shown in Figure 8 are not surprising. They indicate that, on average, the European driver is exposed to lower levels of glare than his English counterpart. Note, however, that the frequency of exposure to very high levels of glare is not much different. Of course, the other part of the question is illumination for visibility. These data are

Figure 8. Frequency distribution of glare intensities at sites on the Continent in Europe.
(From Yerrèll, 1971.)

shown in Figure 9. Clearly, on average, the English drivers enjoyed higher illuminating intensities than did their counterparts on the Continent. Using the average data, one might argue that the British system is better because it provides higher illuminating intensities and no more exposure to very high levels of glare than does the European system. On the other hand, if the French data in Figure 9 were representative of the European system, then we would say it was better, because it provides equivalent illuminating intensities and overall lower glare levels.

It is important to point out that the Yerrell data are not to be taken as definitive. They are nearly 20 years old, the samples are relatively small, and there are a number of other variables to be considered. They are offered here as an illustration of the kind of analysis that I believe is required in order to arrive at really useful conclusions. Yerrell's data were also collected in the real world, so they include effects such as dirt, misaim, problems with the electrical system, etc. that must be considered.

The only comprehensive evaluation system in existence at present is CHESS (Bhise, et al, 1977). I believe it points in the direction that lighting research must take. The job of lighting researchers in the near future is to try to obtain the best possible information for each of the elements in the computer model. We look forward to the challenge.

Figure 9. Comparison of illuminating intensities from British and Continental sites.
(From Yerrell, 1971.)

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