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Development of a Headlighting Rating System

Michael J. Flannagan, The University of Michigan, USA

Christopher Flanigan, National Highway Traffic Safety, USA

1 Introduction

Analyses of accident data indicate that headlamps have considerable potential for increasing traffic safety, and that they should be regarded as important safety equipment. Nevertheless, at least in the United States, drivers appear to be more concerned about glare from headlamps than about the seeing ability they provide. The U.S. National Highway Traffic Safety Administration (NHTSA) is investigating the possible benefits of a headlighting rating system for new vehicles that could be implemented as part of the new car assessment program (NCAP), and which would present information about headlighting to consumers in a format similar to the current NCAP crash avoidance ratings. Such a system might increase consumers' interest in, and knowledge of, the safety potential of headlighting.

The purposes and the background for this effort were described at the PAL meeting that was held two years ago (Flannagan & Sivak, 2001). Since then, the University of Michigan Transportation Research Institute (UMTRI) has been developing a candidate headlighting rating system. After internal review, NHTSA may propose that the system be included in the NCAP, in which case the system would be presented for public comments and would be subject to changes based on those comments. The current paper presents an overview of the safety rationale for the system and discusses how headlighting information might be presented to consumers.

2 The Safety Rationale for the System

A variety of headlighting rating systems have been developed by manufacturers of motor vehicles and of motor vehicle lighting systems, and the development of a rating system at UMTRI has drawn heavily on that work. However, one major distinction between a potential NCAP rating system and rating systems used in industry is that, whereas the industry systems often include consideration of

both driver visual needs and driver preferences, an NCAP system should concentrate on driver visual needs—and in particular how driver visual needs relate to safety.

2.1 Inferring driver visual needs from crash data

Roadway travel at night is much more risky than travel in the day, per unit of distance. The resulting differences in crash statistics between night and day are an important potential source of information about how well headlamps are serving their safety function, and about how they might be improved. However, not all of the differences in risk between night and day are relevant to headlighting. This is because headlighting, by its nature, addresses problems that are caused by the darkness of night, which is only one of several reasons for the increased risk at night. Other reasons include higher use of alcohol, increased fatigue, and a different mix of drivers. None of these differences can be addressed directly by headlighting. Because of this, researchers interested in headlamps and road lighting have tried to separate the effects of light from all other nighttime risk factors.

One recent line of work has used the seasonal variation in natural light from summer to winter and the transitions to and from daylight saving time (DST) in an attempt to isolate the effects of natural light, assuming that most other variables that characterize people's road travel will be linked to clock time rather than to the position of the sun in the sky (Owens & Sivak, 1996; Sullivan & Flannagan, 1999, 2001, 2002). This work has taken advantage of the Fatality Analysis Reporting System (FARS), which is a NHTSA database that includes information on all road crashes in the U.S. that involve at least one fatality. The database has a reasonable level of detail for each crash, including time of day and location.

A central set of results from this work is presented in Table 1, which shows the ratios of rates at which three classes of single-vehicle fatal crashes occurred in the dark and in the light for comparable periods of time before and after the transitions to and from DST in the U.S. For comparison, similar ratios, also from FARS, are shown for the same classes of crashes from a study that examined

differences between night and day rather than dark and light (Burgett, Matteson, Ulman, & Van Iderstine, 1989). Although all of these types of single-vehicle crashes are much more common (per distance traveled) at night, only pedestrian crashes are more common in the dark, when factors such as alcohol and fatigue are controlled for by the DST method. Run-off-road crashes are not significantly affected by light condition, and overturn crashes actually appear to be *reduced* in darkness by a statistically significant amount. It is difficult to imagine a mechanism by which reduced light could prevent overturn crashes directly, but it may be that indirect behavioral mechanisms, such as drivers being more cautious in the dark, are responsible.

Crash Type	Night/Day	Dark/Light
Pedestrian	6.72	4.14
Run off road	6.75	n.s.
Overturn	4.83	0.73

Table 1 Comparisons of ratios for prevalence of three single-vehicle crash types at night and in the day (Burgett et al., 1989) versus in the dark and in the light (Sullivan & Flannagan, 2001). The ratio for run off road crashes in the dark and in the light was not significantly different from 1.0. See text for details.

Detailed examples of the effects of the daylight saving time transition are shown in Figure 1, which displays data from a study by Sullivan and Flannagan (1999) for two specific fatal crash types (single-vehicle, run-off-road crashes on curved rural roads, and pedestrian crashes under more general conditions). The data are from the nine weeks before and the nine weeks after the fall return to standard time, for a one-hour period in the evening that was light before the time change and dark afterward. The crash counts are accumulated from 1987 through 1997. There is clearly a major increase in pedestrian crashes in the dark. In contrast, there is no evidence of an abrupt change in the run-off-road crashes at the return to standard time, although there appears to be a slight, steady decline in those crashes throughout the 18-week period. Because the

decline is steady and does not appear to be influenced by the transition from light to dark it may be attributable to seasonal decreases in exposure over this period, which runs from late August to late December. (The comparable data for the spring, evening change to daylight saving time shows a similar steady *increase* over 18 weeks. Note that in both cases this means that there were more run-off-road crashes in the light than in the dark.) As in the more general analysis conducted by Sullivan and Flannagan (2001), the effects of ambient light appear to be very strong and very specific to pedestrian crashes.

The central importance of pedestrian crashes in the effects of light on safety is just what one would expect from the human factors analysis of the visual capabilities and needs of drivers presented by Leibowitz and Owens (1977). They proposed that at the low levels of illumination that are typical of night driving certain “focal” visual capabilities (such as detecting pedestrians) are significantly impaired, while certain “ambient” visual capabilities (such as the visual guidance needed to steer the vehicle) are relatively well preserved. Furthermore, they suggested that drivers are not fully aware of this selective degradation, perhaps leading to unjustifiably high confidence in their abilities to drive safely at night.

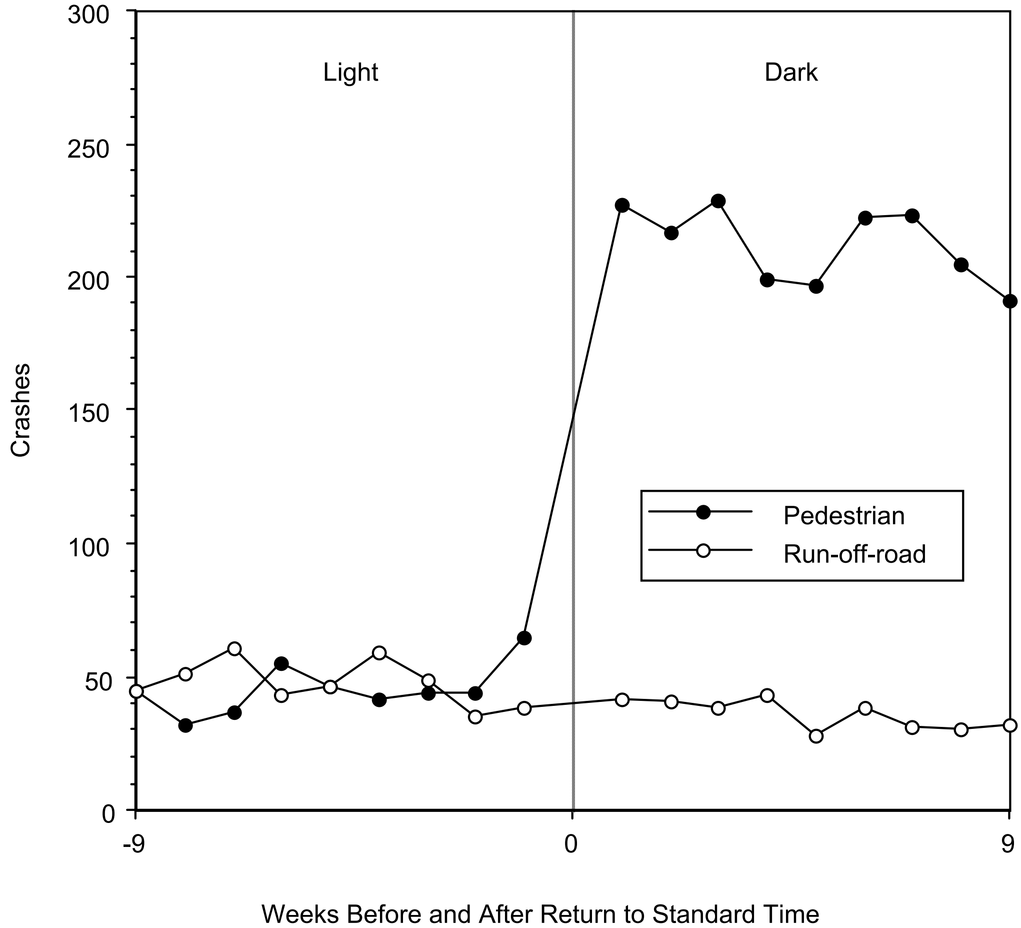

Figure 1. Numbers of pedestrian and run-off-road fatal crashes occurring in the one-hour period in the evening that changes from light to dark at the fall return to standard time, for the 9 weeks before and after the time change. Counts are accumulated over 11 years, 1987 to 1997. See text for more details. Adapted from Sullivan and Flannagan (1999).

Focusing on pedestrian crashes, Sullivan and Flannagan (2001) also considered the interaction of ambient light and posted speed limit. Those results are shown in Figure 2. The dark/light ratio for pedestrian crashes increases substantially with posted speed limit, as one might expect from the consensus among researchers that low-beam headlamps do not provide sufficient seeing distance above about about 45 miles per hour (72 km/h) (Perel, Olson, Sivak, & Medlin, 1983) and drivers' apparent underuse of high beams (Hare & Hemion, 1968). The estimates of lives potentially saved shown

in Figure 2 for roads with various speed limits indicate the safety benefits that would be realized if the rates of pedestrian crashes in the dark could be reduced to the rates of pedestrian crashes in the light.

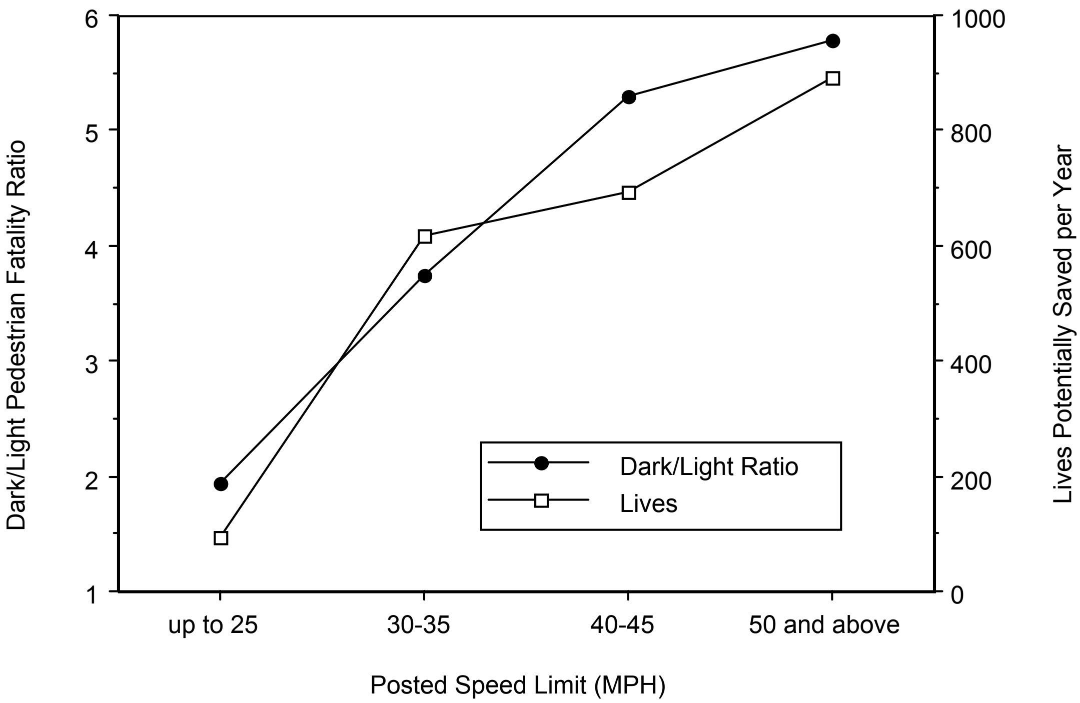

Figure 2. Dark/light pedestrian fatality ratios and lifesaving potential of artificial lighting by posted speed limit. Dark/light ratios are based on 11 years of FARS data (1987-1997); lives potentially saved are based on FARS data for 1999. Adapted from Sullivan and Flannagan (2001).

Three conclusions follow from the analyses of crash data:

(1) There is currently a significant safety problem with darkness that headlamps might potentially address. Specifically, Sullivan and Flannagan (2001) estimate that about 2,300 pedestrians are killed per year in the U.S. because of drivers' inability to see in darkness (i.e., the total of the "lives potentially saved" function in Figure 2). That is therefore the number of lives that could potentially be saved by a perfect headlighting system, one that could in effect turn night into day. How close any realistic headlighting system might come to that ideal is an open question.

(2) The effects of darkness on safety in the kind of single-vehicle crashes that are potentially addressed by headlighting are quite specific. Pedestrian visibility appears to be a problem, but visibility of the roadway itself, as indicated by single-vehicle road-departure crashes, does not appear to be a problem for safety. This may be because the combination of current headlamps and current roadway markings is already virtually ideal in supporting driver vision at night. Alternatively, it is possible that the lack of an effect of darkness is because drivers have continuous information about their ability to see the road and therefore may adjust their behavior when conditions are bad, possibly by slowing down. In contrast, they seldom have any basis to judge their ability to see objects, such as pedestrians, because such objects are very seldom present, and when isolated pedestrians do become visible it is often already too late to react.

(3) The safety problems of darkness appear to be markedly worse at higher speeds, just as would be expected from the consensus of work on seeing distance with low-beam headlamps (Perel et al., 1983).

In summary, safety considerations suggest that headlighting in the U.S. would be improved by providing more light—specifically, more light for seeing pedestrians at greater distances with low-beam lamps.

2.2 Current U.S. headlamp photometrics

Given the photometric limits on headlamps that are already required by Federal Motor Vehicle Safety Standard (FMVSS) 108, we expect that a rating system that encourages greater seeing distances would not result in major changes in the overall distribution of light, but would likely result in proportional increases of light at the key seeing and glare test points in FMVSS 108. For example, Table 2 shows comparisons between some of the most influential low-beam test points in FMVSS 108 and median values from a market-weighted sample of current U.S. low-beam headlamps (Schoettle, Sivak, & Flannagan, 2001). For the test point at 0.5 degrees down and 1.5 degrees right, the current median intensity is in the lower half of the permitted range (13,537 cd). Attempts to increase seeing distance would elevate that value, but could not push it beyond

the maximum of 20,000 cd. The value could therefore be increased by a factor of about 1.48. Light at the glare points (0.5 degrees up, 1.5 degrees left; and 1.0 degree up, 1.5 degrees left) would probably also increase, but would also be limited by the corresponding maximums in FMVSS 108. The maximum increases at those points would therefore be by factors of about 1.41 and 1.56, respectively.

Test Point Locations (degrees)	Current Limits (cd)	25, 50, 75 Percentiles (cd)		
0.5 D, 1.5 R	10,000 – 20,000	11,652	13,537	15,158
1.5 D, 2.0 R	> 15,000	16,151	22,104	27,289
0.5 U, 1.5 L	< 1,000	573	707	962
1.0 U, 1.5 L	< 700	329	448	497

Table 2 Comparisons between photometric limits for selected test points in FMVSS 108 and 25th, 50th, and 75th percentile values for current U.S. low-beam lamps (Schoettle et al., 2001).

2.3 Visual consequences of more light

Consider any night driving situation in which visibility is determined by headlighting (rather than by ambient light) and in which there is an opposing vehicle (i.e., glare is present). There are two light values that are most important: the intensity directed by a driver’s own headlamps toward a stimulus that he or she may need to see, and the intensity directed toward the driver’s eyes by the opposing headlamps. Visibility will be improved by increases in the former or by decreases in the latter. However, consider what would happen if both levels were increased or decreased in tandem. That would be analogous to a situation in which the minimum and maximum light levels specified in headlighting standards, or in a rating system, were all raised or lowered. After a period of adjustment, the light output of a population of lamps could all be proportionately higher or lower. Would visibility improve up to a point as light levels increased, and then decrease as the effects of glare became worse?

Depending on the initial conditions, would increases in light sometimes result in immediate decreases in visibility?

Figure 3 is adapted from a report on the CHESS headlighting model (Bhise et al., 1977), and represents the predictions of that model for visibility of pedestrians, given proportional increases in seeing and glare light. The model uses a representation of the headlamp in question in the form of a candela matrix, along with information about roadway geometry, pedestrian locations, pavement reflectances, and a variety of other variables. For a large number of simulated roadway situations, meant to be reasonably representative of the real world, it uses a visibility model to determine whether a driver would be able to see a pedestrian. The vertical axis of Figure 3 shows the percentage of such situations in which the pedestrian is determined to be visible at a distance great enough to allow a driver time to react. The horizontal axis of Figure 3 represents headlamp intensity as a percent of the output of a typical headlamp. Thus, 100 percent represents the typical lamp and higher and lower percentages can be used to assess the likely effects of overall changes in intensity. In the simulation, the relative distribution of light is fixed, and all values in the candela matrix representing the headlamp are simply adjusted up or down by a common factor.

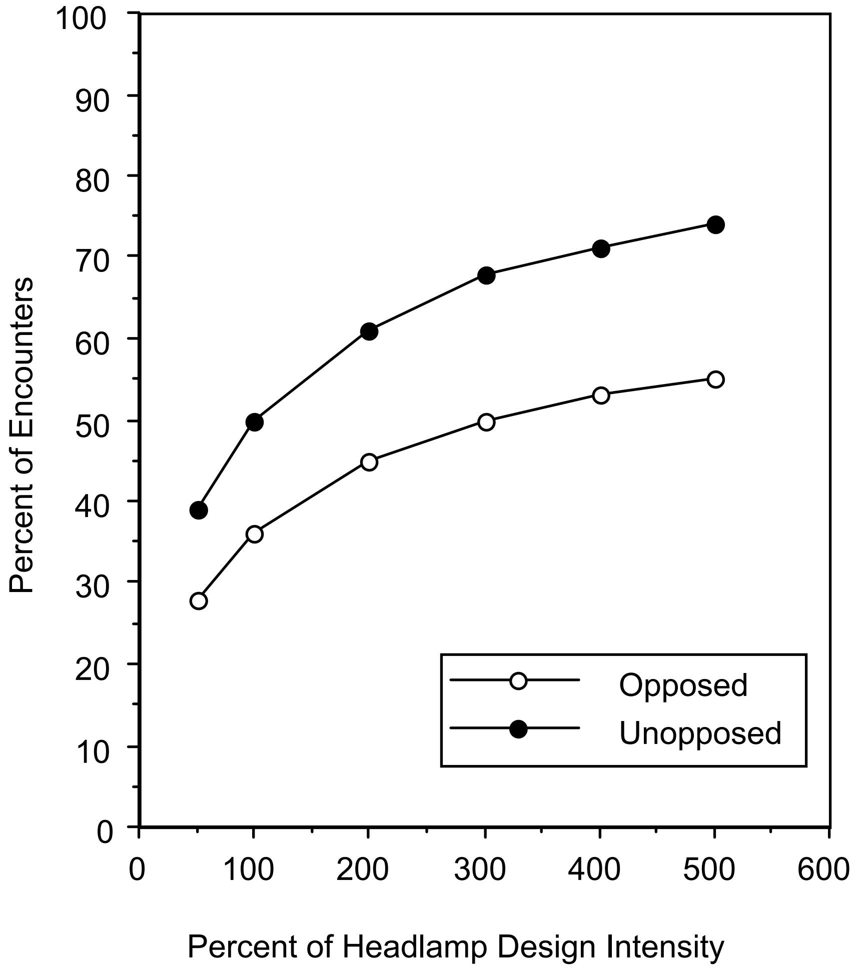

Figure 3. *Effect of headlamp intensity on detection of pedestrians in the CHESS simulation, for cases with and without opposing glare, which is also increased in intensity when present (adapted from Bhise et al., 1977, Figure 4-2).*

Not surprisingly, in unopposed situations visibility increases with more light, although at a diminishing rate. More importantly, however, the same pattern holds even in opposed situations, when the negative effects of increased glare are pitted against increased seeing light. The percent of pedestrians seen in opposed situations is lower than in unopposed situations at each percentage of typical headlamp intensity, but more light always helps overall visibility. In terms of objective seeing ability, stronger headlamps are always better.

However, glare has both objective effects on drivers' ability to see and subjective effects on their comfort. While the objective effects are accounted for in Figure 3, the subjective effects are not. As visibility increases in this sort of

exercise, so does discomfort glare, and—as pointed out by Bhise et al. (1977)—the overall figure of merit in the CHESS system therefore peaks at about 100 percent of typical low-beam intensity. But that peak depends on the relative weights assigned to pedestrian visibility and subjective discomfort in determining the CHESS figure of merit. Different weights would lead to different results.

The key tradeoff involved in low-beam lighting thus appears to be a tradeoff between visibility and comfort. If objective visual performance were the only criterion, there would be no clear upper limit to how intense headlamps should be. Indeed, if optimizing visibility is the goal of a headlighting system designed for meeting situations, it is not clear that low beams in general offer much of an advantage over high beams. For example, Johansson, Bergstörm, Jansson, Ottander, Rumar, and Örnberg (1963) conducted field tests of visibility distances in meeting situations with high (full) and low (dipped) beams, and concluded:

The finding in these experiments . . . means that if visible distance on the near side of the road is taken as the only criterion of efficiency of meeting lights, dipping should never take place, or if it does it should take place later than is now customary. . . . [An] objection is that, although full headlights give greater visible distances, they cause so much discomfort from glare that they are intolerable under normal driving conditions. This may well be so, but if so it must be recognized that the gain of comfort resulting from dipping is obtained at the cost of some loss in visible distance, at any rate until the meeting cars are very close together. (pp. 178-179)

Given the central importance of seeing ability for safety, it is difficult to advocate trading seeing ability for comfort. However, as suggested by Johansson et al., it may be that, although higher intensity headlamps increase seeing ability, there is a level at which people simply will not tolerate the discomforting effects of the glare. It is also possible that at some intensity people's behavior will change in ways that are not reflected in the kind of visibility modeling used in CHESS. For example, people may avert their gaze from the road ahead of them if the glare of oncoming headlamps is above a certain level. How close are current headlamps to such a level?

It appears that the upper limits for glare that might be established based on the behavioral consequences of subjective discomfort would be high relative to the levels of glare that are currently common (with either U.S. or European-style lamps). One of the most comprehensive studies of the discomforting aspects of headlamp glare is work by Schmidt-Clausen and Bindels (1974). Based on that work, Sivak and Flannagan (1993) suggested that the discomforting aspects of glare, considered separately from the effects of glare on objective visual performance, led to a recommended maximum intensity of between 810 and 2,478 cd per lamp (depending on the assumed level of adaptation luminance) at a point 0.25 degrees above and 2.0 degrees to the left of the straight ahead. In a study performed in The Netherlands that included both subjective ratings of discomfort from glare and objective measures of driving performance, Theeuwes and Alferdinck (1996) concluded that glare levels at least as high as current U.S. maximums (which they instantiated as 1,380 cd per lamp) were acceptable.

3 Form of a candidate rating system

3.1 Mechanics of the system

The type of rating system we are contemplating would begin with candela matrices for the low- and high-beam lamps. It would be “vehicle based” in that it would use the photometric measurements along with information about where the lamps are mounted on a vehicle to calculate the overall illumination of a road surface and of objects on that surface. The candidate system is currently implemented in MatLab for Windows. No human judgment is involved; the system simply calculates a variety of values from the photometric description of a headlighting system that it is given. Three main forms of output are generated: (1) the overall rating, (2) several numerical estimates of details of the performance of the headlighting system, and (3) isolux diagrams for the low- and high-beam systems.

3.2 Presentation to consumers

What is the most important information that a headlighting rating system could give to consumers? Crash data suggest that pedestrian visibility is the area in

which improvements in headlighting would yield the greatest safety benefits. Furthermore, pedestrian visibility appears to be most critical on higher speed roads. Consequently, a rating system must be designed to emphasize the seeing distance provided by low-beam headlamps. Although other aspects of headlighting may be important for consumer preference, or may be speculatively related to safety, no other aspect of headlighting has nearly the weight of evidence relating it to safety, or nearly the likely magnitude of an effect on safety. A rating system based on safety needs as outlined here would therefore compute an index of low-beam seeing distance and use it as the primary basis for rating a headlighting system. Although other characteristics would be rated, as shown in Table 3, they would be considered ancillary ratings and no claim would be made in the system that they were important for safety.

Primary rating
Low-beam seeing distance
Ancillary ratings
High-beam seeing distance
Low-beam characteristics:
Width of beams
Light on signs
Glare to oncoming drivers
Foreground irregularity

Table 3. Primary and ancillary ratings

The ancillary ratings in Table 3 are all very easy to compute once one has the photometric information about the headlamps of interest. The candidate versions of the software that we have been working with compute these ratings, and several others as well. However, ease of computation is clearly not reason enough in itself to include extra data in a system designed to provide consumers with useful information. We suggest that the ancillary ratings in Table 3 would be worth providing, although in a clearly secondary form, because they are either of interest to consumers for reasons independent of safety or because there has been reasonable speculation (so far unsupported

by clear evidence) that they are related to safety. Furthermore, including the ancillary ratings in the database developed by the rating system would make them available to researchers and might help clarify their potential relationships to safety.

However, given that there is currently not convincing evidence for the safety importance of the ancillary characteristics, there is not a rational basis to include them with low-beam seeing distance in an overall rating related to safety. Because of the critical importance of longer seeing distances from low beams, it would not be desirable to allow improvements in any of the ancillary characteristics to compensate for lower values of low-beam seeing distances in determining an overall rating. For example, high-beam seeing distance is clearly an important aspect of headlamp performance, but seeing distance with high beams is adequate much more often than with low beams (Rumar, 2002). Wider low-beam patterns are also likely to be beneficial for visibility, in many low-speed situations, but the crash data indicate that those are not the situations with the greatest safety needs. Sign light may be important for legibility of guide signs, and that probably contributes to efficiency and convenience, but there is no clear evidence for a safety problem with current levels of sign light in the U.S. (e.g., Russell, Rys, Rys, & Keck, 1999).

The evidence with regard to glare is that the current levels of glare permitted within FMVSS 108 are not high enough to have negative effects on driver behavior (Theeuwes & Alferdinck, 1996), and that in terms of drivers' objective ability to see, even increases in glare are consistent with improved visibility as long as they are accompanied by increases in seeing light that are at least proportional (Bhise et al., 1977). We therefore argue that it is appropriate to include low-beam glare among the ancillary ratings, leaving the control of glare largely up to FMVSS 108, rather than to combine glare light and seeing light in the primary rating of a headlighting system. Relegating low-beam glare to a secondary role in a rating system may seem counter to the high level of public concern about headlamp glare that seems prevalent now in the U.S., based on responses to a recent NHTSA request for comments (Van Iderstine, 2002). However, the distinction between objective and subjective effects of glare is central to the way glare is the treated in the rating system, and we suggest that

this distinction is also important to convey to the driving public in order for any public discussion of the glare to be properly informed with regard to the issues of comfort, vision, and safety. Also, it appears that many of the negative comments about glare that NHTSA has received have limited implications for the current photometric limits on glare because they result from a variety of circumstances not controlled by the glare limits themselves (the usage and aiming of fog lamps, high-mounted headlamps, the perceived color of high-intensity discharge (HID) lamps, etc.). For example, many of the negative comments received by NHTSA appear to concern glare from HID headlamps, in spite of the fact that HID lamps in the U.S. typically produce less glare light, as measured at the formal test points, than non-HID lamps (Sivak, Flannagan, Schoettle, & Nakata, 2002).

Foreground irregularity appears to be very important in determining consumers' subjective ratings of headlighting (e.g., O'Day, Stone, Jack, & Bhise, 1997). However, the areas that are most critical for that subjective reaction may be too close to the vehicle to be critical for driver reactions. For example, the most important predictor for several aspects of driver's subjective reactions to headlamps from the work by O'Day et al. is the width of the beam pattern at 6 degrees down (from the driver's eye location). For a typical passenger car geometry, that corresponds to a distance of about 8 m in front of a vehicle, or a time of about 0.3 s at 100 kilometers per hour, far too little time for a driver to be able to respond effectively to visual information

Part of the output of the rating system software is a set of isolux contours as shown in Figure 4. Such figures can show a lot of details of low-beam performance, and can vividly illustrate the differences between low and high beams. Such diagrams could be presented to consumers as part of the rating system, although for practical reasons they might be limited to forms of presentation in which a consumer might ask for information on a specific vehicle (e.g., on a web site). The many diagrams that would be necessary, for example, in a brochure covering all vehicles rated for a given year might become unwieldy.

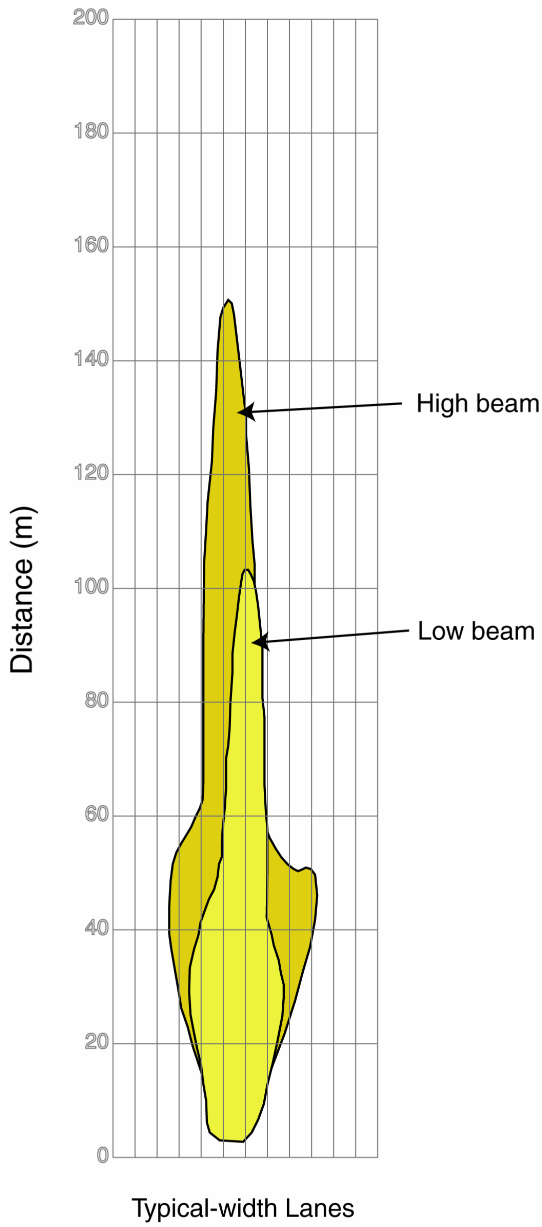

Figure 4. *Example isolux diagram for a specific vehicle (i.e., considering all lamps, as mounted), as it might be presented to consumers, summarizing relative low-beam (lighter shading) and high-beam (darker shading) performance in terms of distance ahead of the vehicle and lane widths.*

4 Expected Effects of a Rating System

The overall effect of a rating system is expected to be an increased emphasis on the importance of seeing distance with low beams. This should result in improvements in safety, primarily in the form of fewer pedestrian collisions. There will probably also be some increases in glare light from low beams, although the restrictions on glare in FMVSS 108 should keep any increases at acceptable levels. For control of both glare light and seeing light, consumers should be advised that overall headlighting performance depends strongly on proper headlamp maintenance, especially for vertical aim. Information provided with a rating system about the importance of vertical aim might result in the greatest possible improvement in driver vision (Sivak, Flannagan, & Miyokawa, 1998). Information provided to the driving public about the form of a rating system and the reasons for its emphasis on low-beam seeing distance should increase public awareness of the need for more light from low beams. That in turn may increase the public’s understanding of the tradeoffs between seeing and glare, and may make drivers more willing to tolerate some level of discomfort from glare in exchange for increased seeing distance and safety.

People also may be better informed about the differences in seeing distance between low and high beams, and this may make them more aware of the need to use high beams when it is appropriate. Data from the U.S. in the 1960s showed a substantial underuse of high beams in situations without opposing traffic (Hare, & Hemion, 1968), and a recent follow-up indicated that the current situation is still about the same (Sullivan, Adachi, Mefford, & Flannagan, 2003). The inappropriate use of low beams may be a result of a general lack of understanding on the part of the driving public of how critical headlighting is for safety.

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