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16. Abstract

In 2001, NHTSA opened a public docket requesting comments from the public regarding headlamp glare. Most responses received have been complaints. NHTSA initiated research to address these complaints and to determine causes and effects of headlamp glare. In 2005, Congress authorized NHTSA to "conduct a study on the risks associated with glare to oncoming drivers, including increased risks to drivers on 2-lane highways, increased risks to drivers over the age of 50, and the overall effects of glare on driver performance" including "recommendations regarding measures to reduce the risks associated with glare to oncoming drivers." This report summarizes research on headlamp performance, visibility, glare, and safety conducted to address the issues identified by Congress and by NHTSA through review of public comments. These research activities included a state-of-knowledge report; a pilot study using naturalistic methods to assess relationships among glare, driving behavior and crash risk; analyses to compare the effects of headlamp characteristics on visibility and glare; preliminary assessments of headlamp illumination and aim on real-world lighting conditions; a review of visual needs regarding visibility and glare and metrics for characterizing them; a field experiment to characterize recovery of older drivers following exposure to headlamp illumination; and demonstration of a prototype safety-based adaptive forward-lighting system with potential to reduce glare while maintaining visibility, by decreasing intensity toward nearby drivers.

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ABSTRACT

In 2001, the National Highway Traffic Safety Administration (NHTSA) opened a public docket requesting comments from the public regarding headlamp glare. Most responses received have been complaints. NHTSA initiated research to address these complaints and to determine causes and effects of headlamp glare. In 2005, Congress authorized NHTSA to "conduct a study on the risks associated with glare to oncoming drivers, including increased risks to drivers on 2-lane highways, increased risks to drivers over the age of 50, and the overall effects of glare on driver performance" including "recommendations regarding measures to reduce the risks associated with glare to oncoming drivers." This report summarizes research on headlamp performance, visibility, glare, and safety conducted to address the issues identified by Congress and by NHTSA through review of public comments. These research activities included a state-of-knowledge report; a pilot study using naturalistic methods to assess relationships among glare, driving behavior, and crash risk; analyses to compare the effects of headlamp characteristics on visibility and glare; preliminary assessments of headlamp illumination and aim on real-world lighting conditions; a review of visual needs regarding visibility and glare and metrics for characterizing them; a field experiment to characterize recovery of older drivers following exposure to headlamp illumination; and demonstration of a prototype safety-based adaptive forward-lighting system with potential to reduce glare while maintaining visibility, by decreasing intensity toward nearby drivers.

I. EXECUTIVE SUMMARY

Introduction

In 2001, NHTSA opened a public docket requesting comments from the public regarding headlamp glare, in response to informal concerns it had received focusing on glare from high-intensity discharge (HID) headlamps and from trucks and sports/utility vehicles (SUVs). The more than 5,000 responses that have been received to date largely consist of complaints regarding glare and NHTSA initiated research to address these complaints and to determine causes and effects of headlamp glare (Bullough et al., 2003; Singh and Perel, 2004; Akashi et al., 2005, 2008; Jenness et al., 2008).

By headlamp glare, several different responses to bright lights can be meant. Disability glare is a reduction in visibility caused by scattered light from a light source in the field of view that acts as a contrast-reducing "veil" over the visual scene. Discomfort glare is the annoying or painful sensation that can accompany the presence of a bright light in the field of view. Finally, glare recovery is the period of time following the presence of a bright light, during which visibility is temporarily reduced. Each type of glare can have different effects on drivers.

In 2005, the U.S. Congress passed and President Bush signed the "Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users" (SAFETEA-LU) bill, authorizing the U.S. Department of Transportation (DOT) to implement programs for ground transportation. Section 2015 of SAFETEA-LU authorized DOT to "conduct a study on the risks associated with glare to oncoming drivers, including increased risks to drivers on 2-lane highways, increased risks to drivers over the age of 50, and the overall effects of glare on driver performance" including "any recommendations regarding measures to reduce the risks associated with glare to oncoming drivers."

The present report, in conjunction with three accompanying reports (NHTSA, 2007; Akashi et al., 2008; Bullough et al., 2008) summarizes the research on headlamp performance, visibility, glare, and safety conducted through NHTSA to address the various issues identified by Congress in SAFETEA-LU and by NHTSA through its study of headlamp glare in response to public comments. These activities included:

- A state-of-knowledge report summarizing knowledge about the issues identified in SAFETEA-LU by Congress and the concerns of the driving public;
- A pilot study using naturalistic driving methods to assess the links among headlamp glare, driving behavior, and crash risk;
- Analyses to compare the relative effects of different headlamp characteristics on visibility and glare to oncoming drivers along two-lane highways;
- Preliminary assessments of headlamp illumination and aim characteristics on real-world vehicle samples;
- A review of visual needs regarding visibility and glare while driving at night, and metrics for characterizing those visual needs;
- A field experiment to characterize visual performance of older drivers following exposure to headlamp illumination; and

- Development and evaluation of a prototype safety-based adaptive forward-lighting system (SAFS) with the potential to reduce glare while maintaining visibility by decreasing headlamp intensity toward nearby drivers.

In this chapter of the report, the logic behind the specific research tasks above and their relationships to the information requested by Congress in SAFETEA-LU, and to the comments received by NHTSA's public docket on glare, are described. Because there is a broad range of issues related to headlamp glare (NHTSA, 2007), the approach taken in these studies was to cover a range of these issues in breadth.

Organization of This Report

The current section of this report, entitled "Introduction and Summary," serves as an executive summary for all of the studies that were conducted to address Congress's requests regarding the study of headlamp glare and driving performance. The research approach is described, as well as a summary of the methods, results, and implications of the findings of each research task. Some of the research tasks were preliminary or exploratory in nature, using novel research methods; in such cases, the conclusions from the research should be taken as tentative or suggestive pending independent validation.

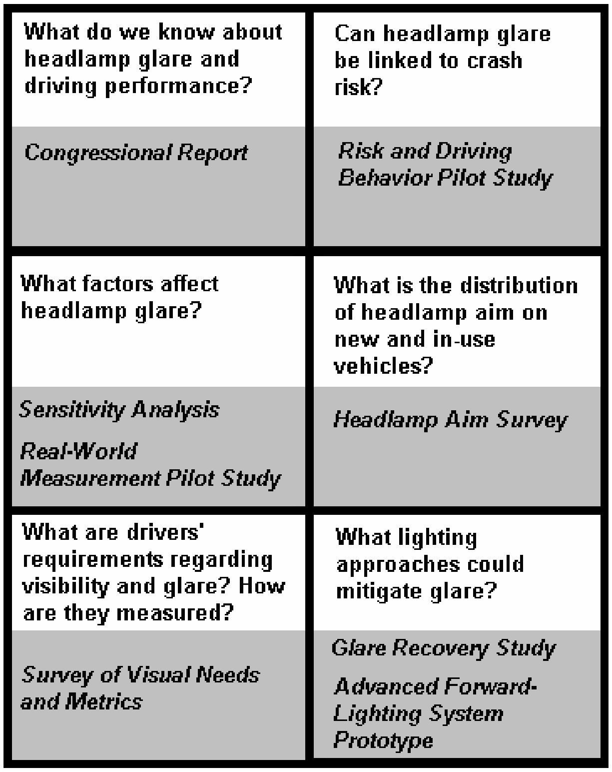
Some of the research tasks are described in detail in separate reports accompanying the present report; these include the state-of-knowledge report delivered to Congress in 2007 (NHTSA, 2007); sensitivity analyses of the impacts of headlamp characteristics on glare and visibility on two-lane highways (Akashi et al., 2008); and the documentation of the development, evaluation and demonstration of the SAFS prototype (Bullough et al., 2008). The remaining tasks are described in individual subsequent chapters of the present report.

Logic of the Research Studies

As mentioned above, the research tasks were selected to address a series of questions that follow from the Congressional directive to study headlamp glare in SAFETEA-LU and that address the concerns described by the public in their comments to NHTSA. Three groups of research studies were performed to address the following issues:

- Headlamp glare and safety – *Can headlamp glare be linked to crash risk?*
- Causes of headlamp glare – *What factors influence the likelihood of causing headlamp glare?*
- Countermeasures for headlamp glare – *How can headlamp glare be reduced or avoided, and visibility be maintained?*

Figure I-1 illustrates these three general topic areas as three rows in a matrix; each matrix cell contains a question and a shaded portion that refers to one of the tasks carried out through the present research program. The two columns of the matrix in Figure I-1 represent, from left to right, increasing levels of specificity in addressing the three topic areas listed above. For example, in the second row, the sensitivity analyses and real-world headlamp illumination pilot survey are conducted to identify, in a "big picture" manner, which characteristics of headlamps are predictive of glare, whereas the preliminary survey of headlamp aim was performed to obtain specific data on the distribution of headlamp aim properties (since previous research [NHTSA, 2007] suggested that this factor was relatively important in predicting glare).



What do we know about headlamp glare and driving performance?	**Can headlamp glare be linked to crash risk?**
Congressional Report	*Risk and Driving Behavior Pilot Study*
What factors affect headlamp glare?	**What is the distribution of headlamp aim on new and in-use vehicles?**
Sensitivity Analysis *Real-World Measurement Pilot Study*	*Headlamp Aim Survey*
What are drivers' requirements regarding visibility and glare? How are they measured?	**What lighting approaches could mitigate glare?**
Survey of Visual Needs and Metrics	*Glare Recovery Study* *Advanced Forward-Lighting System Prototype*

Figure I-1. *Matrix of research questions addressed by NHTSA's forward lighting research program.*

Each of the information areas in the matrix in Figure I-1 (the three topic areas listed above, for two levels of specificity) are addressed in the present chapter of this report by:

- Converting the issue from Figure I-1 into a research question;
- Describing the relationship between that question and the Congressional information request in SAFETEA-LU;
- Providing a brief, non-technical summary of the methods used to address the question and the key findings of each study; and
- Presenting a short answer to the research question.

Following the summary of each of the research tasks using the structure outlined above, the implications and recommendations of the overall research study findings are presented.

Subsequent chapters of the present report will summarize in technical detail the execution, results, analyses, and discussion of the following research tasks:

- Risk and Driving Behavior Pilot Study (Chapter II)
- Preliminary Survey of Real-World Headlamp Illumination (Chapter III)

- Preliminary Survey of Headlamp Aim (Chapter IV)
- Survey of Driver Visual Needs and Metrics (Chapter V)
- Field Study of Visual Recovery Following Exposure to Glare (Chapter VI)

Each of these subsequent chapters is designed to be read more or less as a stand-alone document; much like the accompanying technical reports that are associated with the present research program on vehicle forward lighting and glare. They are included as chapters within the present report rather than as separate documents because of the often novel or exploratory research methods used that might limit the interpretation of the resulting findings. Nonetheless, all of the research activities that are described either in this report, or in separate reports, have reduced uncertainties regarding the causes, effects, and countermeasures for nighttime glare from vehicle headlamps.

Q: What is the State of Knowledge Regarding Headlamp Glare?

Many of the comments received by NHTSA regarding headlamp glare, as described above, were complaints regarding the high intensity from headlamps, particularly from "bluer" colored headlamps (largely assumed to be HID headlamps) and from light trucks and SUVs. Previous research (Bullough et al., 2003) has demonstrated that when producing an equal light level at one's eyes, HID headlamps are more uncomfortable than halogen headlamps, although the degree to which they reduce visibility is equal.

The overall purpose of the section of SAFETEA-LU addressed by the present report was to study the risks associated with glare to oncoming drivers, with focus on increased risks along two-lane highways, increased risks for older drivers, and overall effects on driving performance. As the research studies were in preparation, NHTSA delivered an initial report to Congress (NHTSA, 2007) addressing these issues.

In short, headlamp glare reduces visibility by creating a "veil" of scattered light over the visual scene inside the eye. Glare is more critical on two-lane than on multi-lane highways, because the generally lower light levels on two-lane highways increases the effect of the scattered light in the eye, because there is less separation between oncoming vehicles and a driver's line of sight, and because two-lane roads are less likely to have markings that improve lane-keeping. Glare reduces visibility more for older (>50 years) drivers because the eyes of older drivers contain more dead cells that increase the amount of scattered light compared to younger drivers, resulting in a brighter "veil" over the scene. Glare also increases discomfort to drivers, which might be related to poorer steering control, lane-keeping, and speed control. Despite the very clear evidence relating glare to reduced visibility, there is little direct evidence linking glare to increased crash risk. This is because unlike drug or alcohol use, there is usually no way to determine precisely whether or how glare might have contributed to a crash. Yet some police reports of crashes do mention glare as a potential cause of crashes, and it is not unreasonable to expect that the reductions in visibility caused by headlamp glare increase crash risk.

A: NHTSA's initial report to Congress (2007) summarizes these issues in a question-and-answer format, describing the primary gaps in information that prevent clearer associations between headlamp glare and crash risk.

Q: (How) Can Headlamp Glare Be Linked to Crash Risk?

The instruction from Congress regarding headlamp glare in SAFETEA-LU requests information on the risks of glare. Obviously, if headlamp glare and the complaints that NHTSA has received about it are merely an inconvenience rather than a real safety issue, the entire issue of headlamp glare might not be worth studying. As described in the initial report to Congress (NHTSA, 2007), indirect evidence can be found to link glare to crashes. There is little doubt that glare reduces visibility, and reduced visibility, albeit in a context unrelated to glare, appears to be related to the risk of crashes involving pedestrians along rural roadways (Sullivan and Flannagan, 2002).

As part of the present research program, a pilot study was carried out to determine the feasibility of linking headlamp glare to crash risk using naturalistic driving data collection methods (described in Chapter II of the present report). The logic is based on a series of hypotheses and inferences constructed in the form of a logical syllogism: first, that drivers exhibit different behavioral responses when driving in locations that have inherently high crash risk than they do when they are driving in locations with inherently low crash risk. The second hypothesis is that the same drivers will exhibit some of the same behaviors when they are exposed to oncoming headlamp illumination that they did when they were driving in high-risk locations. The inference that could be derived if these hypotheses were confirmed is that oncoming headlamp illumination is associated with increased risk.

The field experiment was performed using ten subjects driving an instrumented vehicle through two intersections of two-lane State highways, sometimes driving straight through the intersections and sometimes making left-turn maneuvers. Through global positioning satellite (GPS) technology and by tying into the vehicle's on-board computer, data regarding vehicle speed, throttle, and braking could be measured and stored by a data logger. The data logger also recorded light levels facing out through the windshield and light levels near drivers' eyes, measured using head-worn sensors that subjects wore while performing the experiment. The head-worn device also contained an accelerometer so that it could record head movements.

The hypotheses were tested using multiple linear regression models relating driver responses and behaviors to the risk levels and light levels experienced during each experimental session. Because of the exploratory character of the pilot study, a statistical significance probability criterion of 0.1 was used. Both the variability in throttle position and the overall amount of head movement were associated with higher risk and with the level of oncoming headlamp illumination, lending credibility to the hypotheses. To independently test the second hypotheses, a second field experiment was conducted along a rural roadway with confederate vehicles presenting different levels of headlamp illumination to subjects. Neither throttle variability nor overall head movement were statistically significantly associated with oncoming light level, although the direction of the effects were the same as in the previous experiment.

This pilot study was a preliminary look at whether driving behaviors and responses could be linked to quantitative crash data at different locations and to light levels from oncoming headlamps. The effects that were measured were generally weak in nature, as driving is an activity with much inherent variability from moment to moment. Nonetheless, the results of this modest pilot study are encouraging in that they suggest that subsequent experimental investigations might confirm the hypotheses explored in the present pilot study.

A: Comparisons of driver behavior in locations differing in crash risk and under different levels of oncoming headlamp illumination suggest that some of the same behaviors associated with higher crash risk could be associated with oncoming headlamp illumination. If these findings can be validated, they suggest that headlamp glare might be able to be linked to increased risk of crashing, but a solid affirmative conclusion cannot yet be drawn.

Q: What Factors Affect Headlamp Glare?

The direction from Congress in SAFETEA-LU regarding headlamp glare requests the study of its effects on two-lane highways, hopefully leading to recommendations for measures to reduce the risks of glare in such situations. Additionally, many of the public comments that have been received by NHTSA regarding headlamp glare have requested that NHTSA take action to reduce headlamp glare for the driving public. In order to understand what countermeasures might be most helpful at reducing the negative effects of glare (e.g., reduced visibility and increased discomfort), a series of sensitivity analyses were conducted to determine what factors might contribute to these negative effects (Akashi et al., 2008). A sample of headlamp beam patterns representing different vehicle and lighting characteristics were selected for analysis:

- Light Source: Halogen and high-intensity discharge (HID) headlamps
- Mounting Height: Passenger car and light truck/sports utility vehicle (SUV) headlamps
- Optics Type: Reflector-based headlamps and projector-based headlamps
- Beam Pattern: Visual/optical aim left (VOL) and visual/optical aim right (VOR) headlamps
- Aim: Correct aim, downward mis-aim (headlamps pointed slightly down) and upward mis-aim (headlamps pointed slightly up)

The headlamps were analyzed using computer calculation and simulation tools to determine, for an average driver, the detection distance to targets along a straight two-lane highway under different headlamp types and aim conditions, the brightness of the contrast-reducing scatter in the eye caused by different oncoming headlamp types, and the discomfort experienced by a driver exposed to these different conditions.

In general, the analyses revealed that the HID headlamps studied, on average, tended to produce longer detection distances than the halogen headlamps (although some halogen headlamps produced longer detection distances than some HID headlamps). This finding is consistent with the generally positive opinions that people who own vehicles with HID headlamps have about this type of technology (Jenness et al., 2008). The headlamps with higher mounting heights (i.e., on trucks/SUVs) also tended to produce longer visibility distances than those with shorter mounting heights (i.e., on passenger cars). There also tended to be a conflict between detection distances and glare, in that the headlamps that provided longer detection distances tended to result in more scattered light in the eyes of oncoming drivers and therefore, more discomfort. Differences found between optics types and beam patterns were small, and not always consistent in direction. Downward mis-aim of headlamps reduced detection distances, and upward mis-aim of headlamps increased scattered light and discomfort to oncoming drivers. When headlamps were mis-aimed, differences between some headlamp types decreased. This suggests, for example, that upwardly mis-aimed halogen headlamps could have negative effects as large as upwardly mis-aimed HID headlamps.

Because the sensitivity analyses described above involved experimental manipulation of the variables such as lamp type, mounting height, and headlamp aim, the results of the study cannot be directly applied to a real-world driving situation. In order to begin to understand how some headlamp characteristics interact in the real world to influence oncoming headlamp illumination that can produce glare, a novel measurement apparatus was developed and deployed along a roadway intersection to measure the characteristics of illumination from oncoming vehicles' headlamps (see Chapter III of the present report).

The apparatus consisted of a camera to capture an image of an oncoming vehicle headlamp, a calibrated illuminance and chromaticity meter to measure light levels in the direction of a hypothetical oncoming driver, two vertical arrays of photosensors to measure the relative vertical illuminance profile from oncoming vehicle headlamps, and an infrared laser range-finder that measured the distance to oncoming vehicles and signaled to the other equipment to perform simultaneous measurements. All of the data for each vehicle were stored on a laptop computer that executed custom software to perform measurements and store data autonomously.

Over 100 vehicles were measured during the pilot study data collection. By simultaneously measuring the headlamp height, the height of the maximum vertical gradient in light level from the headlamps, and the illuminance toward a hypothetical oncoming driver, it was possible to determine, for the limited sample of vehicles measured, the distribution of headlamp mounting heights, the distribution of estimated vertical aim angles (albeit imprecisely), and the distribution of light levels that would be experienced by oncoming drivers. The factor most related to the light level reaching the eyes of an oncoming driver was headlamp aim, and there was relatively little influence of headlamp mounting height although there were relatively fewer headlamps with mounting heights above 85 cm, thought to be more problematic for glare (headlamps are permitted to have mounting heights between 56 and 137 cm). Because of the limited vehicle sample, only a few of the 100+ headlamps used HID light sources. Despite the preliminary nature of the measurements and the small sample size, the apparatus that was developed appears to provide a useful and efficient technique for measuring real-world vehicle headlamp illumination.

A: The results of the sensitivity analysis and the limited data from the real-world headlamp measurement pilot study suggest that several factors influence glare, including mounting height and light source type, but that maintaining proper headlamp aim is probably the factor that is most strongly and consistently related to glare.

Q: What is the Distribution of Headlamp Aim on In-Use and New Vehicles?

As described above, the direction from Congress in SAFETEA-LU regarding headlamp glare is to identify recommendations for reducing the effects of glare, and the driving public would appear to desire reductions in glare as well. Evidence from the sensitivity analyses that were conducted (Akashi et al., 2008) as well as from the real-world measurement of oncoming headlamp illumination (Chapter III) suggests that headlamp aim is an important factor related to glare and visibility when driving at night. Previously published research also reinforces the importance of this factor in influencing both glare and visibility (Perel, 1985; Sivak et al., 1998).

The pilot study of real-world headlamp illumination measurement had some imprecision regarding the distribution of headlamp vertical aim, but the causes of this imprecision (e.g., vehicle loading, uneven tire pressure, or suspension condition versus improperly aligned headlamps) could not be ascertained. Nor could any information be determined about whether vehicle headlamps became mis-aimed over a period of time, or if the headlamps on some new vehicles might be mis-aimed when the vehicle is purchased. To begin to identify possible countermeasures for reducing the effects of mis-aimed headlamps, some information regarding the causes of mis-aim is necessary. Using a modified version of a portable headlamp aim setting device that was calibrated to allow the determination of vertical mis-aim (up or down) for visual/optically aimed headlamps, the aim status of the left and right low beam headlamps from a sample of 100 in-use vehicles and 20 new vehicles was measured (see Chapter IV of the present report).

Of the in-use vehicles measured, 62 percent had at least one headlamp mis-aimed outside the tolerance suggested by the Society of Automotive Engineers (SAE) for aim (aimed up or down more than 0.8º from proper position). There were more vehicles with downward aim than with upward aim. Of the new vehicles measured, 30 percent of them had at least one headlamp mis-aimed. While not related to glare, it was observed that from one out of eight to one out of five of the in-use vehicles had headlamps that were damaged, dirty, or exhibited condensation.

Again, the sample size was quite limited, but the evidence suggests that the majority of the new vehicles measured (about two thirds) had both headlamps properly aimed, whereas most of the in-use vehicles measured had at least one mis-aimed headlamp. If these findings could be validated for a larger vehicle population, they would suggest that requiring newly sold vehicles to have properly aimed headlamps would not eliminate headlamp mis-aim; improper aim is more likely to be caused when the vehicle is in use.

A: Headlamp mis-aim was found on the majority of in-use vehicles measured, and although on average more downward mis-aim was found, upward and downward mis-aim were both common in the sample population evaluated. The majority of the new cars measured had both headlamps aimed properly.

Q: What Do Drivers Need From Headlamps? How Can These Needs Be Measured?

Headlamp glare is the focus of most of the public comments to NHTSA regarding headlamps, and the focus of Congress's information request in SAFETEA-LU. In theory, it is possible to eliminate headlamp glare completely, by simply eliminating headlamps. Naturally, such a solution is not realistic. Driving at night is essential to society, and the purpose of headlamps, and of low-beam headlamps in particular (since these are designed to be used in the presence of oncoming traffic) is to provide drivers with enough light to see but not so much light that the safety of oncoming drivers might be overly compromised.

To this end, a review of drivers' visual needs and metrics for defining them was conducted (see Chapter V of the present report) to identify, when possible, common threads among many of the research studies that have been performed to identify how much light is needed to see when driving at night, and how much light toward other drivers is too much (e.g., reduces visibility or creates unacceptable discomfort). Importantly, the metrics for defining these visual needs were also surveyed so that methods for evaluating solutions identified in the current study (i.e., the safety-based AFS prototype described in Chapter VI) could be performed.

In summary, present standards for headlamp performance (Federal Motor Vehicle Safety Standard [FMVSS] 108) include minimum intensities to ensure sufficient visibility and maximum intensities to protect against creating glare. Most drivers use their low-beam headlamps most of the time (Sullivan et al., 2004), but the evidence suggests that low beams are insufficient to detect and respond to potential roadway hazards at driving speeds greater than about 30 to 40 mph (48 to 64 km/h) (Johansson and Rumar, 1968). In areas with high ambient light levels such as city downtowns, low-beam headlamps appear to provide enough light to see, because driving speeds are lower in urban areas and because ambient light levels (from street lighting or other sources) are usually higher. Low beam intensities might even be able to be reduced in these areas to reduce glare to other drivers without strongly affecting forward visibility. Modifications to low beam patterns have been suggested and demonstrated to provide incremental benefits in terms of visibility, but light levels comparable to those from typical high-beam headlamps appear to be desirable in terms of forward lighting, particularly for faster driving speeds. Yet these same light levels would almost certainly be undesirable by drivers facing them in nighttime driving situations.

The current U.S. low beam pattern specified by FMVSS 108, in general, provides an acceptable level of glare in many driving conditions that have been studied (with the caveat that most of the conditions studied have simulated straight, flat highways). A factor not extensively studied when assessing glare is the color of headlamps and the levels of discomfort they elicit. Prior research has found that the "bluer" color of HID headlamps increases discomfort (although it does not appear to affect reductions in visibility from glare), and most of the research has used halogen or incandescent headlamps with a "yellower" color appearance than HID headlamps.

A potentially feasible approach to dynamic headlamp systems that are beginning to be available on the market, therefore, could be a beam pattern with substantially higher intensity than typical low-beam headlamps, but with the ability to reduce intensity in a local geometric region corresponding to the position of nearby drivers' eyes.

The studies that were reviewed primarily used the distance at which targets (such as pedestrians) could be detected by a driver as a visibility metric, and the reduction in detection distance of the same targets by oncoming headlamps as a disability glare metric. However, some studies have used reaction times as a metric for visibility (and increases in reaction times to quantify disability glare), and there is ample evidence to suggest that these different metrics are functionally equivalent. Evidence also suggests that it is the "dosage" (the product of illuminance and duration of light exposure) of light from oncoming headlamps that primarily influences glare recovery times following exposure to headlamp illumination. Regarding discomfort glare, subjective ratings from individuals are at present the best and most reliable way to measure this response.

A: Present low beam headlamp patterns do not appear to provide sufficient visibility to see and react to potential roadway hazards at driving speeds higher than 30 to 40 mph (48 to 64 km/h), except in areas with high levels of ambient lighting (i.e., urban areas). Yet, higher intensities will be deemed unacceptable by most drivers facing such headlamps in oncoming situations.

Q: What Lighting Approaches Could Mitigate Glare?

The work described thus far demonstrates that any number of potential countermeasures for reducing the negative effects of glare is available. Some of the countermeasures involve comprehensive changes to the requirements for headlamps, and others involve technological developments that might change how headlamps are implemented on vehicles. In the present section of this report, two research activities are described that touch upon both of these kinds of countermeasures.

The first research activity described presently is a field study to assess glare recovery in older (50 and older) and younger (younger than 50 years) drivers (see Chapter V of the present report) to determine whether previous research findings, which suggested that recovery times are related to the "dosage" of light exposure experienced from oncoming headlamps. Different age groups were studied to address Congress's questions about older drivers and glare from SAFETEA-LU and because many of the responses from older drivers to NHTSA's request for public comments were particularly negative. The earlier studies used abstract lighting conditions, but the present study simulated the illuminance profile experienced while passing an oncoming vehicle's headlamps along a two-lane highway. In this study, a projector light source was used that could be controlled to produce a dynamic profile of light, increasing and then decreasing in a similar manner as the light from oncoming headlamps would. Subjects were seated in the driver's seat of a passenger car, and following the presentation of the simulated oncoming headlamp profile, a target located randomly in the field of view was presented, and subjects were asked to respond as soon as they detected the target by releasing a button on a hand-held controller. After each trial, subjects were asked to rate the discomfort they experienced from the simulated headlamp profile.

As might be expected, subjects took longer to detect targets (that is, to recover from the effects of the glare) when the dosage from the simulated headlamp profile was highest. Profiles that had very different peak illuminance values but equivalent dosages resulted in nearly equivalent detection times. The ratings of discomfort, on the other hand, were related to the peak illuminance produced by the simulated profiles. The older subjects took significantly longer than the younger subjects to detect the targets, although their ratings of discomfort were nearly the same as those of younger subjects in this study. Overall, the results of the field study showed that in addition to experiencing greater disability glare in the presence of headlamp glare (because of increase scattered light in the eye), older drivers are also likely to have reduced visual sensitivity than younger drivers for a longer period of time, following the presence of headlamp glare.

The implications of the study in terms of countermeasures are that the specification of maximum intensity values at discrete points within a headlamp's beam pattern will not necessarily ensure that drivers will experience short glare recovery times. This is because an oncoming driver's eyes pass along an entire angular region of the beam pattern as two vehicles pass each other along a highway. Specification of the integrated (summed) values throughout the segment would be more likely to provide control for glarer recovery, but would involve headlamp light measurement procedures that are more complex than those currently used to determine if a headlamp meets the FMVSS 108 requirements. A simple technological countermeasure for maintaining visibility following exposure to headlamp illumination might be a retractable, narrow, clear but shaded visor that reduces oncoming headlamp intensity (and therefore, the dosage) along narrow band within which many oncoming vehicle headlamps are likely to be positioned.

The glare recovery field study described above used actual calculated low-beam headlamp illuminance profiles as the simulated headlamp conditions in the study. Because the review of driver visual needs (Chapter IV) suggested that headlamps with higher intensities than low beams produce would improve visibility, a prototype safety-based adaptive forward-lighting system (SAFS) was developed (Bullough et al., 2008), evaluated, and ultimately demonstrated on a moving vehicle. The objective of the SAFS prototype was to provide a headlamp beam pattern comparable to high-beam headlamps (based on an analysis of driver visual needs) in terms of forward visibility, but comparable to low-beam headlamps in terms of glare. The prototype used projector-type headlamp modules, customized to accept a baffling shield in the focal plane of the projector system that could project a shadow pattern onto the illumination pattern produced by the headlamp. [Importantly, the functionality of the prototype is not limited to the specific embodiment studied in the present project; reduction of intensity could be carried out through a modular approach of smaller sources (e.g., possibly light emitting diodes) that each contribute to a portion of the overall headlamp distribution at any given time.]

In a dynamic system, the shields within the prototype modules would move to the location of an oncoming or preceding driver. The SAFS prototype was evaluated initially using subjective ratings to determine the maximum size of the shadowed region that would be accepted by drivers with such a headlamp system. Then, using reaction times as the primary metric, the forward visibility from the SAFS prototype was compared to conventional high and low beams, and was found to be similar to that from high-beam headlamps (except in the shadowed region, which had visibility similar to that of low beams). The glare characteristics were assessed by measuring reaction times and subjective ratings of discomfort, with the result that the prototype SAFS resulted in lower glare to oncoming drivers than conventional high beams. Finally, the prototype system was installed onto a passenger car and demonstrated under dynamic conditions. Subjective impressions from the evaluators confirmed that the system has the potential to permit higher light levels in the visual scene that can also be reduced in local regions when other drivers are present, while requiring no greater space in the front of a vehicle than a conventional headlamp system.

The initial evaluation of the SAFS prototype was preliminary and relatively simplistic. Nonetheless, the basic feasibility of such a system was demonstrated, and the SAFS approach of dynamic glare reduction would appear to address driver's visual needs in terms of forward visibility and glare.

A: Changing headlamp standards to account for glare recovery would be relatively complex, and older drivers will always have longer recovery times than younger ones, so older drivers should be the basis for any recommendations for changes. As a longer-term solution, the approach embodied in a safety-based AFS prototype could be a basis for providing increased light levels for driver visibility, while decreasing intensity locally to control glare to other drivers.

Conclusions

The research activities undertaken in the present research program and described in subsequent chapters of this report and in other reports (NHTSA, 2007; Akashi et al., 2008; Bullough et al., 2008) have provided information that can reduce uncertainty regarding the effects of glare, particularly along two-lane highways and for older drivers, as requested by Congress and as suggested by many of the public comments NHTSA has received on the topic in the past several years. Undoubtedly, subsequent research will be required in order to confirm the present findings with more certainty; this is due in part to the novel methods, apparatus, and approaches that were used in many of the research studies summarized here as well as the limited samples in several of the studies. Nonetheless, the results, especially taken in light of previous research, point toward several tentative conclusions:

- Headlamp glare is quite probably related to increased risks for drivers because of the abundant published evidence that glare reduces visibility and because research is beginning to establish a role of visibility in safety. Present findings suggest that drivers may engage in some of the same driving behaviors when exposed to headlamp illumination that they do when they are driving in locations with higher crash risk.
- Older drivers are more susceptible to headlamp glare in terms of disability glare and glare recovery.
- Drivers' perceptions of glare (i.e., discomfort glare) are often different from the other negative effects of glare (i.e., disability glare and glare recovery), probably explaining in part the negative responses to "blue" HID headlamps (because they elicit greater discomfort even when they do not diminish visibility more than halogen headlamps [i.e., at the same luminous intensity]).
- The preponderance of mis-aimed headlamps, even in the small sample sizes used in these studies, suggests that more consistently correct headlamp aim could improve visibility and reduce glare conditions by creating more consistent visual conditions for drivers using them, and facing them.
- Present low beam headlamp patterns do not appear to provide sufficient visibility at many of the higher driving speeds for which they are commonly used, even when no oncoming vehicle headlamps are present.
- Dynamic approaches to forward lighting such as that embodied in the SAFS prototype developed through this program do have promise for glare reduction while maintaining good forward visibility.

Based on these limited studies and on the published literature summarizing existing knowledge, the types of countermeasures for reducing headlamp glare that were discussed in NHTSA's (2007) report to Congress were judged as having high, medium or low potential to reduce glare or improve visibility as follows:

- Mounting height: ***low*** - Reducing headlamp mounting heights might slightly reduce glare, but might also slightly reduce forward visibility.
- Aim: ***high*** - It appears that some new vehicles and many in-use vehicles have mis-aimed headlamps that compromise visibility (when mis-aimed downward) and increase glare to other drivers (when mis-aimed upward). Periodic adjustment of aim should result in more consistent visual conditions.
- Optical design: ***low*** - Within the limitations of a headlamp system that produces basically a low beam pattern, there is little evidence that this factor plays a large role in the amount of glare experienced by drivers.
- Low beam distribution: ***low*** - If headlamps are constrained to producing a pattern similar to a low beam under a broad range of driving conditions with glare control as a primary design consideration, much of the evidence suggests that further improvements will be incremental. (Most evaluations of low beam distributions, however, have assumed straight, flat roads; improvements to low beams under more complex conditions have only rarely been studied.)
- Adaptive beam distributions: ***high*** - Dynamic approaches such as that used in the SAFS prototype can significantly change the landscape regarding glare and visibility, but will involve investment from the vehicle lighting industry, higher consumer costs, and longer times to achieve improvements.
- Color: ***medium*** - "Bluer" sources such as HID headlamps do indeed increase discomfort, so restricting short-wavelength output could reduce discomfort, but would likely have little impact on visibility reductions from headlamps.
- Cleaning and maintenance: ***medium*** - From 10 percent to 20 percent of vehicles in the small sample measured in the present study had headlamps that were dirty, damaged, or had condensation inside the front lens. In practice, cleaning and maintaining headlamps should not be difficult, and from prior research, should improve forward visibility and reduce glare to other drivers, even if only modestly.

II. RISK AND DRIVING BEHAVIOR PILOT STUDY

Summary

Despite the logical connection between visibility during nighttime driving and safety, and the abundant evidence that headlamp glare reduces visibility, there is little direct evidence linking headlamp glare to crash risk. The present report describes a study conducted to explore the relationship between headlamp illumination and crash risk based on driving behavior. Two signalized intersections with similar appearance, but differing in terms of crash history, were selected as study locations. Study participants drove through each intersection several times, either driving straight through the intersection or making a left-turn maneuver. The vehicle driven by subjects was instrumented to measure vehicle speed, throttle position, brake pedal status, and vertical illuminance at the location of the interior rear-view mirror. During trials, subjects wore a headset that contained an accelerometer for measuring head movements, and was outfitted with light meters to measure corneal light exposure. Data were recorded at 100 Hz using a data logger. Subjects also estimated their level of risk using a subjective rating scale during each pass through one of the intersections. Subsequent analyses of the resulting data using multiple linear regression modeling revealed that several driving behaviors were modestly related to crash risk, as well as to light exposure parameters, consistent with a link between headlamp glare and crash risk. A follow-up study using the same subjects was conducted using confederate vehicles (vehicles driven by experimenters that were encountered by subjects in the study) equipped to produce low and high levels of headlamp illumination to determine whether the regression models could be used to make *a priori* predictions of the relevant driving behaviors in the presence of different headlamp illumination levels. Although the small sample sizes in the study resulted in modest statistical relationships, the results suggest that headlamp glare and crash risk are indeed related.

Introduction

Despite the logical connection between visibility during nighttime driving and safety, and the abundant evidence that headlamp glare reduces visibility, there is little direct evidence linking headlamp glare to crash risk (NHTSA, 2007). Recent NHTSA research has demonstrated the degree to which headlamp illumination from oncoming and following vehicles reduces the visibility of potential safety hazards in and along the roadway while driving at night (Bullough et al., 2003; Akashi et al., 2008), increases the discomfort to drivers exposed to such illumination (Bullough et al., 2003), and results in reduced visual function following headlamp exposure (Van Derlofske et al., 2005). Exposure to headlamp illumination also appears to have some impacts on driving behaviors that are associated with stress (Steyvers and DeWaard, 2000), distraction (Lansdown et al., 2004) and fatigue (Summala et al., 1999), such as reductions in speed and lateral drifts in lane position (Bullough et al., 2005), although these links were identified through *post hoc* analysis of a subset of data from NHTSA's 100-car naturalistic driving study (Neale et al., 2002) and not based on *a priori* predictions.

Evidence linking exposure to headlamp illumination from oncoming or following vehicles to crash risk is important because the study of headlamp glare by an organization such as NHTSA, whose purpose is to assess and improve driving safety, should be demonstrated to have implications for safety. Certainly, glare from vehicle headlamps has been cited in a small percentage of crashes as a possible related factor (Hemion, 1969). On the other hand, it has been demonstrated that if all drivers used their high-beam headlamps consistently, visibility when approaching and passing oncoming vehicles would be improved compared to if they used their low-beam headlamps (excluding conditions such as fog or snow when high-beam headlamps would be problematic), even though sensations of visual discomfort would increase (Bergstrom, 1963; Helmers and Rumar, 1975; Flannagan et al., 2000), a finding that would seem to be inconsistent with the expectation that headlamp glare reduces safety. At any rate, the relationship between headlamp glare and crash risk, if any, is not a simple one.

This chapter of the present report describes a study conducted to explore the relationship between headlamp illumination and crash risk based on driving behavior. In particular, the specific research questions investigated in the present study include:

- What (if any) driving behaviors are associated with locations having increased crash risk?
- What (if any) driving behaviors are associated with increased corneal light exposure from oncoming headlamp illumination?
- Do the answers to the previous questions result in overlap in the types of behavioral responses that are associated with both crash risk and exposure to headlamp illumination?
- Can *a priori* predictions of these driving behaviors be made in an experimental context?

In essence, this pilot study was carried out to determine the feasibility of linking headlamp glare to crash risk using naturalistic driving data collection methods. The logic is based on a series of hypotheses and inferences constructed in the form of a logical syllogism: first, that drivers exhibit different behavioral responses when driving in locations that have inherently high crash risk than they do when they are driving in locations with inherently low crash risk. The second hypothesis is that the same drivers will exhibit some of the same behaviors when they are exposed to oncoming headlamp illumination that they did when they were driving in high-risk locations. The inference that could be derived if these hypotheses were confirmed is that oncoming headlamp illumination is associated with increased risk.

The details of the study methods, apparatus, and findings are outlined below, but in several ways the proposed study builds upon an earlier study (Rackoff and Rockwell, 1974) that explored the influence of fixed roadway lighting and crash risk at intersections with different crash rates. Rackoff and Rockwell (1974) reported that the rate of vehicle deceleration when entering intersections was more rapid for higher-risk intersections than for lower-risk intersections. Rackoff and Rockwell used maneuvers such as driving straight through intersections and making left-turns through the same intersections. Such maneuvers would seem to have obvious risk-related differences, and therefore differences between intersections might only be seen for one type of maneuver.

In addition to the specific research questions listed above, which pertain to the objective of identifying stronger links (if possible) between crash risk and headlamp glare, an overarching goal of the present study is to identify driving behavior responses that can be readily measured and that are relevant to headlamp illumination exposure or crash risk, and to develop data analysis methods for assessing relationships among driving behavior, crash risk, and headlamp glare.

Methods

Procedure

Two intersections in the Albany, New York, region were identified as being similar in terms of appearance, number of lanes, signalization and relative surroundings. Each intersection was a four-way intersection with two-lane roads approaching from all four directions. At each intersection, only one of the turn lanes had a left-turn arrow, while the other three did not. Both intersections were in suburban neighborhoods with limited commercial properties adjacent to the intersection and no pedestrian facilities. The State highways both had speed limits of 45 mph and the county highways had speed limits of 30 mph. Table II-1 summarizes the most recent available crash history data for each intersection (for calendar years 2004 and 2005) based on information provided by the New York State Department of Transportation (NYSDOT). Only the total number of crashes are given; no data regarding the cause of crashes are available. By several measures (total number of fatal crashes, crashes per million vehicle miles driven, and crash severity), one of the intersections (of NYS Rte. 146 and County Rte. 88 in Saratoga County, denoted intersection 1) had a lower risk of crashes and lower crash severity distribution (evidenced by the lower average crash cost) than the other intersection (on NYS Rte. 29 and County Rte. 47 in Saratoga County, denoted intersection 2), even though it has approximately double the traffic density as the other intersection. Figures II-1 and II-2 show aerial views of each intersection. The two intersections are classified by NYSDOT as being the same type of intersection (rural, signalized intersections with no access control) and on this basis would be expected to have similar distributions of crash severity.

Location	**Average annual daily traffic**	**Number of crashes (% at night)**	**Number of fatal crashes**	**Crashes per million vehicle miles**	**Average crash cost**
1: Rte. 146 & Rte. 88	17,000	21 (24%)	0	3.37	$114,000
2: Rte. 29 & Rte. 47	8100	30 (23%)	1	5.12	$382,000

Table II-1. *Crash data summary for the two locations in the initial study.*

Ten subjects participated in the pilot study. Subjects were asked if they were familiar with the intersections prior to the study, and were asked how often they drove through the target intersection (daily, weekly, monthly, rarely, or never). Since the subjects reported driving through these intersections rarely if ever, all subjects were familiarized with each intersection by driving through it four times prior to the data being collected.

Figure II-1. *Daytime aerial view of intersection 1 (from Google Earth^{TM}).*

Figure II-2. *Daytime aerial view of intersection 2 (from Google Earth^{TM}).*

During the study, each subject wore a head-worn illuminance meter (described below) while driving through the intersection. The paths that the subjects drove through were identical, consisting of four straight paths (through the intersection directly) and four left turns. An experimenter was seated in the passenger seat next to the subject, and the subject was asked to rate their risk perception after they drove through the intersection each time. The question asked was “How risky do you perceive this intersection” with a risk rating of 1 ("not at all risky") to 5 ("very risky") being the range of responses. The experimenter recorded the response immediately after it was made. Subjects were instructed to give an integer rating value. No other intersections other than the two used in the study were evaluated by subjects.

The intersections were not close enough to each other that most subjects could readily drive through both of them on the same night, so all subjects except one drove through the two intersections on two separate nights. One subject, who missed the first experimental session in which he was supposed to participate, drove through both intersections on the same night in order to complete the study. The study was counterbalanced such that five of the subjects drove through intersection 1 before intersection 2 and the other five drove first through intersection 2 and then through intersection 1.

All of the trials were conducted after dark, during March and April 2008, between the hours of 8 p.m. and 11 p.m.

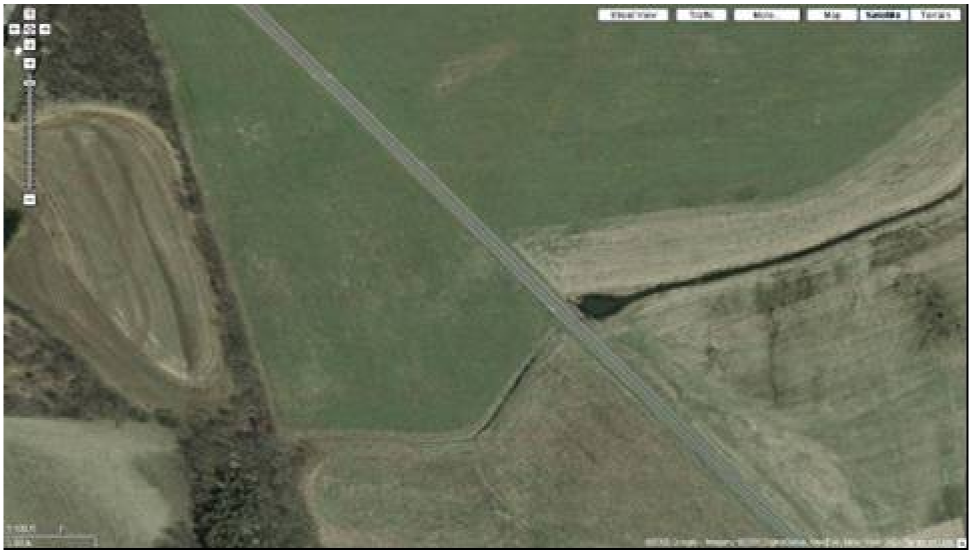


Figure II-3. *Aerial view of the rural road segment used for the follow-up study (from Google Maps^{TM}).*

Following completion of the study described above, a brief follow-up study was conducted using 9 of the same 10 subjects who participated in the first study. This study took place along a straight, flat section of a rural road (on County Rte. 137 in Rensselaer County; Figure II-3). Each subject drove along this roadway in both directions. Two confederate vehicles of the same make and model year (2008 Mazda 6) were parked along either end of the straight segment so that as the subject and experimenter approached the segment, the experimenter discreetly called a cell phone in one of the confederate vehicles so as not to alert the subject about the impending presence of the confederate vehicle. The confederate vehicle and the test vehicle would meet near the center of the straight segment during each pass along the segment. One of the confederate vehicle's headlamps (confederate vehicle 1) were covered with 50 percent neutral density filters so that the oncoming illuminance from the headlamps was low; the other confederate vehicle's headlamps (confederate vehicle 2) were unfiltered and the rear trunk was loaded with about 400 lbs. of cinder blocks, sandbags, and barbell weights, raising the apparent vertical aim of the headlamps by approximately one degree so that the oncoming illuminance from the headlamps was high. Experimenters' observations confirmed that the headlamps of confederate vehicle 2 were noticeably brighter than those of confederate vehicle 1, but neither confederate vehicle's headlamps appeared impossibly dim or bright. The peak illuminances measured at subjects' eyes during each trial (see "Apparatus" below; generally these values correspond to the oncoming illuminances from the confederate vehicles) averaged 0.9 lx for confederate vehicle 1 and 2.1 lx for confederate vehicle 2.

Because County Rte. 137 is not a State highway, crash statistics are not collected for this road. Because the segment used for the follow-up study is rural, straight, flat, and has little observed traffic, the level of crash risk is assumed to be low. At any rate, since all trials during this latter study occurred at the same location, the crash risk level was presumed to be not only low, but constant.

The order and direction in which subjects experienced each confederate vehicle was counterbalanced as much as possible among the nine subjects. During most, but not all trials, the only oncoming vehicles experienced by subjects were the confederate vehicles.

Apparatus

Several types of data were collected for each subject during both studies: vehicular data, photometric data, and subject behavioral response data. The experimental car was a 1999 Ford Contour that was equipped with a data logger (Race Technologies, DL-1). The logger used contains a global positioning system (GPS) unit and automatically stored location coordinate data. In addition to vehicle speed and position data (which could be estimated from the GPS coordinates), the throttle’s position and brake activation status were also recorded directly from the vehicle or vehicle's on-board computer and recorded by the data logger. Data were measured and recorded at 0.01-second intervals (100 Hz).

The photometric data collected consisted of the subjects’ light exposure (measured from an illuminance meter [Hagner] fixed to the car at the drivers’ eye level behind the interior rear view mirror; the windshield on the test vehicle was not tinted along the top) and the light exposure close to the subjects' eyes, measured by a head-worn illuminance meter developed and constructed by the Lighting Research Center (the Daysimeter [Bierman et al., 2005]). The head-worn device included a photopic illuminance detector and a short-wavelength ("blue") detector. As reported by Bullough et al. (2005), the combination of these two detectors allowed differentiation among light sources of differing spectral composition (i.e., halogen versus high-intensity discharge [HID] headlamps). The fixed-location illuminance meter was baffled so that it did not receive light from overhead (e.g., from roadway luminaires as the vehicle drove underneath a light pole in locations with fixed roadway lighting). Figure II-4 shows a profile of the photopic illuminance measured near the eye in one of the experimental trials; several distinct peaks can be observed that are similar to those reported by Bullough and Van Derlofske (2005).

The subjects' response data included subjective ratings of risk perception and the subjects’ head movements (characterized by the output of an accelerometer mounted to the head-worn illuminance meter). All of the subjects' response data were recorded simultaneously with the vehicular and photometric data by the data logger with the purpose of determining subsequently whether any of the measured driver behaviors could be correlated with any of the photometric measures or risk-related characteristics.

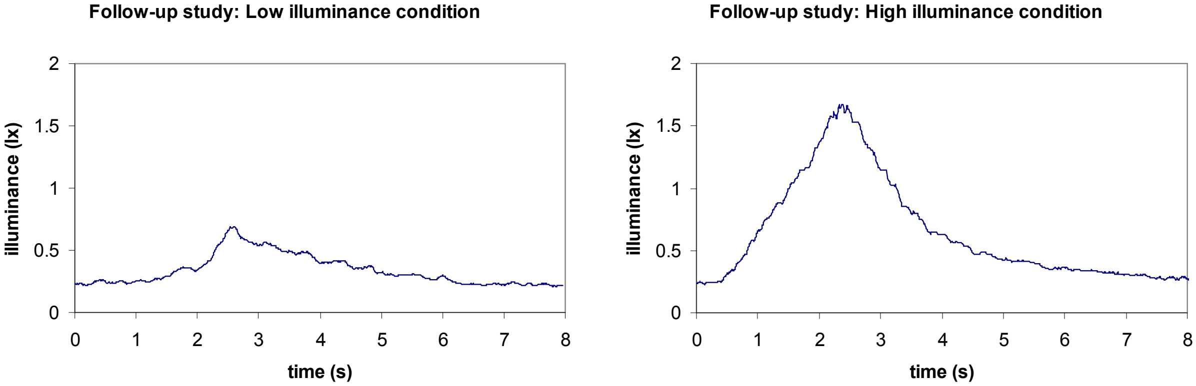


Figure II-4. *Photopic illuminance during similar intervals of the follow-up study. Left: low oncoming illuminance condition; Right: high oncoming illuminance condition.*

The analog measurements recorded by the data logger (e.g., throttle position, illuminance values) were converted from voltages to the actual quantities measured by using computer software. This conversion was performed in the laboratory after the data had been recorded and downloaded.

For the initial study, all of the data corresponding to a distance of 76 m (250 ft) from the center of each intersection was used in the analyses; for the follow-up study, all data along the straight portion of the road illustrated in Figure II-3 were used.

Results

The results of the two studies and initial analyses on the resulting data are summarized in this section of the present report.

Initial Study

In order to assess the relationships among the driving behaviors that were measured using the data logger, the crash risk data from NYSDOT, and the lighting measurement data, multiple linear regression (MLR) modeling (Sheskin, 1997) was conducted. MLR modeling has the advantage of being able to account for several potentially relevant predictors (Sheskin, 1997) of driving behavior, since it is unlikely that such behavior would be predicted by only one variable. In particular, the analyses were conducted to determine to what extent different factors might depend upon the crash risk of each location and upon the light exposure characteristics experienced by the study subjects.

The data that were considered for the regression analysis included:

Variables used as predictors of driving behavior (independent variables):

- photopic eye illuminance (mean, standard deviation and maximum value during each trial)
- short-wavelength ("blue") eye illuminance (mean, standard deviation and maximum value during each trial)
- photopic illuminance as measured from a fixed location on the interior rear-view mirror position (mean, standard deviation and maximum value during each trial; since the other illuminance measurements were made using head-worn gear, it was thought that the illuminances could differ when driver head orientation differed from straight ahead)
- the risk level of the intersection (since only two locations were studied and since intersection 1 was judged as having higher crash risk based on multiple criteria [e.g., crash rate, severity distribution] than intersection 2, this was effectively a binary variable)
- the type of maneuver being performed by subjects during each trial (either driving straight through the intersection or making a left-hand turn)

Variables used as measures of driving behavior (dependent variables):

- vehicle speed (mean and standard deviation [the latter indicating variability in speed] during each trial)
- throttle status (mean and standard deviation during each trial)
- brake pedal status (percentage of time during each trial the brake pedal was pressed)
- head movement acceleration (mean, standard deviation and maximum absolute value during each trial)

When the standard deviation of variables such as photopic eye illuminance or vehicle speed is calculated, this variable provides an indication of the variability of light levels experienced during a trial, or of the variability in driving speed during a trial.

Several of the variables were multicollinear; that is, several pairs of variables were correlated with one another and therefore could result in unreliable or unstable regression models if both variables were included in the models. To assess multicollinearity, the variance inflation factor (VIF; Minitab, 1998; NIST, 2003) was calculated; VIF is a unitless quantity. Variables in regression models that have VIF values of 5 or greater are likely correlated with others and can lead to unreliable regression modeling (Minitab, 1998). Examples of multicollinear variables frequently identified in the MLR models were, unsurprisingly, the photopic and short-wavelength eye illuminance values, and both of these values with the fixed-location illuminance. The photopic eye illuminance was used as the primary measure of light exposure (although a combination of photopic illuminance and output from the short-wavelength sensor could be used to represent spectral sensitivity for discomfort glare [Dee, 2003]). Removal of the short-wavelength illuminance and the fixed-location illuminance removed the multicollinearity from the models. In order to retain some information from the fixed-location and short-wavelength illuminance sensors, two independent variables taking the ratios of the maximum fixed-location illuminance and the maximum short-wavelength illuminance to the maximum photopic eye illuminance were created and added to the models, as their presence did not result in any large VIF values (none of the VIF values exceeded 2.1). The former ratio could be an indication of the driver's direction of gaze when high oncoming illuminances are present (since the illuminance sensors would not be pointed in similar directions if the driver's head is turned toward the side, resulting in a higher ratio of illuminances). The latter ratio could be an indication of whether

HID headlamps produced any substantial levels of oncoming illumination during a particular trial, since the ratio would be higher when light from HID headlamps is incident on it than when light from halogen headlamps is.

Table II-2 summarizes the MLR models. Because of the small sample sizes and data sets, and the preliminary nature of the research study, a probability criterion for of 0.1 was used to determine statistical significance.

Because of the exploratory nature of the present study, specific hypotheses regarding the relationships between crash risk and light exposure conditions and the individually measured driving responses (e.g., speed, head movements, subjective ratings) were not put forward, although, for example, it might be reasonable to expect speed to be lower at the higher-risk location, and the negative value in the cell in Table II-2 corresponding to the column entitled "Crash risk level" and the row entitled "Mean speed (mph)" indicates that in general, the speed was lower at the location with the higher risk level.

Rather, the purpose of the study was to determine whether any of the measured responses could be shown to be related to both crash risk and oncoming headlamp exposure. If so, then the logical inference that oncoming headlamp exposure and crash risk are associated would be easier to make. (Of course, the pilot nature of the experiment should limit the conclusiveness of any such inferences.)

Interactions among independent variables were not assessed in this preliminary study. This is because some of the independent variables had only two levels (e.g., risk level, driving maneuver performed) and the resulting interaction terms were similar in quantity to the independent variable values.

	Independent variables (*shaded cells indicate statistical significance; p<0.1)					
Dependent variables:	**Crash risk level**	**Driving maneuver (straight or left)**	**Mean eye illum. (lx)**	**Std. dev. eye illum. (lx)**	**Short-wavelength illum. ratio**	**Fixed illum. ratio**
Percentage brake time **(%)** **R-sq:** **R-sq (adj.):**	2.56	9.52*	-0.41	0.94	-0.04	-0.15
Mean speed (mph)** **R-sq:** **R-sq (adj.):**	-0.24	-5.64*	-0.07	-0.25	0.08	-0.04
St. dev. speed (mph) **R-sq:** **R-sq (adj.):**	0.64	1.01*	-0.004	0.11	-0.04	0.03
Mean throttle **R-sq:** **R-sq (adj.):**	-0.39	-0.11	-0.18	0.08	-0.03	0.06
St. dev. throttle** **R-sq:** **R-sq (adj.):**	1.21*	1.49*	-0.17*	0.11*	-0.06*	0.06*
Av. head accel.** **R-sq:** **R-sq (adj.):**	0.004*	0.01*	-0.001	0.001*	-0.0001	0.00004
St. dev. head accel.** **R-sq:** **R-sq (adj.):**	0.003	0.01*	-0.001	0.001*	-0.0003	0.0002
Max. head accel.** **R-sq:** **R-sq (adj.):**	0.06*	0.06*	-0.001	0.01	-0.002	0.001
Risk rating** **R-sq:** **R-sq (adj.):**	0.10	0.29*	0.07	0.01	-0.003	-0.005

Table II-2. *Summary of coefficient values for the MLR models in the initial field study (*shaded cells indicate statistical significance with p<0.1; **if a dependent variable name is shaded, the overall regression model was statistically reliable with p<0.1).*

In general, the subjects' responses are most reliably distinguishable between the two types of driving maneuvers (driving straight through, or making a left-hand turn through, the intersection). Since a left turn is associated with greater risk, the MLR coefficient values using the other independent variables can be compared to those predicted by the type of maneuver. The signs of the coefficient values for the crash risk independent variable are always the same as those for the maneuver independent variable as shown in Table II-1, indicating that variability in speed, average head movement, and the maximum head movement acceleration values were higher at the higher-risk location. Similarly, the signs of the coefficients for risk and turn maneuver were consistent for the variability in photopic eye illuminance, except for one dependent variable (mean throttle status), which was not statistically significant. However, the coefficients for the mean eye illuminance independent variable almost always were opposite in sign to those for the variability of eye illuminance. In retrospect, this may be attributable to the overall light levels at intersection 1, with the lower crash risk characteristics, were higher than those at intersection 2 owing to the presence of outdoor fixed lighting associated in part with a convenience store near this intersection. Since the initial expectation was that the overall light level would be indicative of more (or more frequent) oncoming headlamp exposure, the presence of fixed lighting might have confounded this independent variable in some way. Thus, the variability of eye illuminance might be a more accurate predictor of oncoming headlamp illumination than the mean eye illuminance. Indeed, the MLR models described in Table II-2 are consistent with this explanation.

It was observed by the experimenters during the study that the presence of high-intensity discharge headlamps during the study was very rare and that almost all oncoming headlamps experienced by the subjects were halogen headlamps. That, combined with the strong multicollinearity among all of the illuminance data measured in this study, calls into question the practical significance of the short-wavelength and fixed-location illuminance coefficient values, particularly for the variability in throttle status, where these two independent variables were seen as statistically significantly related to the outcome.

In general, then, the results of the initial field study as summarized in Table II-2 are consistent with the notion that drivers may exhibit certain responses and behaviors in locations with increased crash risk, including:

- increased throttle variability;
- increased head movement; and
- increased maximum head-movement acceleration.

Further, the first two responses listed above also appear to be elicited by oncoming headlamp exposure, assuming that variability in eye illuminance is a reasonable surrogate for such exposure.

Follow-Up Study

Since the MLR models summarized in Table II-2 are based on the results of a single experiment, and since an objective of the present study was to determine whether such responses might be considered as useful indicators of increased crash risk in order to relate headlamp glare to risk, the follow up study was considered an important test of the model predictions.

Table II-3 summarizes the coefficient values in the MLR models for the follow-up study. Since there was only one location, and only straight driving was used, neither crash risk level nor type of driving maneuver could be used in the models. Also, since subjects were not made aware that the confederate vehicles were not random encounters during the follow-up study, subjects were not asked to rate their perception of risk as in the initial study.

The data from the follow-up study was a much smaller set than generated during the initial study; subjects each drove along the test site only twice rather than eight times during the previous experiment. Although neither the mean nor variability in photopic eye illuminance were found to be statistically reliable predictors for the dependent variables, the signs of the coefficient values for these independent variables in the MLR models for the follow-up study were consistent with the expectation that these variables might be associated with higher crash risk as identified in Table II-2. Comparing the dependent variables under the low oncoming illuminance conditions with those under the high oncoming illuminances using Student's t-tests showed statistically significantly (p<0.05) higher maximum head acceleration under the higher oncoming illuminances than under the lower oncoming illuminances. None of the other dependent variables revealed statistically significant differences between the low and high oncoming illuminance conditions. These findings, while insufficient to draw firm conclusions, are promising regarding the overall approach, should they be replicated with a larger sample size.

	Independent variables (*shaded cells indicate statistical significance; p<0.1)			
Dependent variables:	**Mean illum. (lx)**	**St. dev. illum. (lx)**	**Short-wavelength illum. ratio**	**Fixed illum. ratio**
Percentage brake time (%) **R-sq:** **R-sq (adj.):**	22.46	10.50	7.66	-9.66*
Mean speed (mph) **R-sq:** **R-sq (adj.):**	-4.04	-2.54	12.00*	-4.01
St. dev. speed (mph) **R-sq:** **R-sq (adj.):**	-0.84	0.03	-0.12	-0.95
Mean throttle **R-sq:** **R-sq (adj.):**	2.72	1.59	-3.96	1.96
St. dev. throttle** **R-sq:** **R-sq (adj.):**	1.43	0.09	-1.62	2.27*
Av. head accel. **R-sq:** **R-sq (adj.):**	0.01	0.01	-0.02	-0.003
St. dev. head accel. **R-sq:** **R-sq (adj.):**	-0.02	0.01	-0.03	-0.02
Max. head accel.** **R-sq:** **R-sq (adj.):**	0.49	0.16	-0.32*	-0.11

Table II-3. *Summary of coefficient values for the MLR models in the follow-up field study (*shaded cells indicate statistical significance with p<0.1; **if a dependent variable name is shaded, the overall regression model was statistically reliable with p<0.1).*

As in the initial study, the practical significance of the statistical reliability of the short-wavelength and fixed-illuminance ratios as independent variables in some of the models is not well understood and could be a spurious finding. Otherwise, the results of the follow-up study are encouraging in that they appear to be consistent with those of the initial study in terms of the direction of effects, if not statistical significance.

Discussion

The research questions to be addressed by the present pilot study were as follows:

- What (if any) driving behaviors are associated with locations having increased crash risk?
- What (if any) driving behaviors are associated with increased corneal light exposure from oncoming headlamp illumination?

- Do the answers to the previous questions result in overlap in the types of behavioral responses that are associated with both crash risk and exposure to headlamp illumination?
- Can *a priori* predictions of these driving behaviors be made in an experimental context?

Although the present study was exploratory in nature, limiting the ability to draw firm conclusions from the resulting data, the results were quite consistent between the two experiments and with previously published research (Rackoff and Rockwell, 1974; Bullough et al., 2005).

To address the first three questions, the results indicate that increased variability in throttle position, overall amount of head movement while driving, and the maximum acceleration of head movement might be associated with driving in locations with increased crash risk. Of these three driver behavioral responses, two – variability in throttle position and overall amount of head movement – also appear to be associated with oncoming headlamp illumination. Again, while it is premature from the results of this modest study to state definitively that these responses are indeed related, if these findings can be validated in future work, then the resulting inference that headlamp glare and crash risk are related appears possible. It is worth noting that Bullough et al. (2005) found a similar relationship between variability in oncoming illuminance and variability in driving speed (which should be related to throttle position).

Again, the follow-up experiment was of limited size and scope and there was an overall lack of statistically significant relationships between many of the independent variables and the dependent variables in that experiment. These limitations make it difficult to state unambiguously that the procedures and analyses employed here can be used to make *a priori* predictions regarding headlamp glare and crash risk. Certainly, it is encouraging that the direction of the effects was consistent between the two experiments.

Regarding the design and execution of similar experiments in the future, the present findings also support the use of some kind of control maneuver, such as the left-hand turn employed in the present study and by Rackoff and Rockwell (1974), in studies of driving behavior related to crash risk and environmental variables. Rackoff and Rockwell (1974) found that drivers' eye positions were more variable when turning left than when driving straight through an intersection, which is consistent with the greater degree of head movements found in the present study when turning left.

Nonetheless, the results of the present study, despite their limitations, lend some tentative credibility to the logical inference that headlamp glare increases crash risk during nighttime driving (NHTSA, 2007). If this inference can be confirmed with additional experimental evidence, then it would appear altogether reasonable to expect that countermeasures for headlamp glare (such as those discussed in Chapter I of this report) might reduce crash risk.

III. EXPLORATORY MEASUREMENTS OF REAL-WORLD HEADLAMP ILLUMINATION

Summary

Despite the increasing identification from the public of headlamp glare as an important problem when driving at night, there are few data available upon which to characterize the levels of headlamp illumination reaching the eyes of drivers of other vehicles that might produce glare. Many studies related to glare from headlamps have used relatively new, properly aimed headlamps systems adjusted to representative mounting heights. Even when headlamp characteristics such as aim and mounting height are adjusted empirically, justification for the parameters used and the resulting glare-related responses is sparse. The present report summarizes the development and initial deployment of a system that can be mounted along an intersection, curve, drive-thru, or parking facility to efficiently gather relevant data about headlamp illumination patterns that might relate to glare. The system can run autonomously to collect many vehicles per data collection period. The system includes a laser range finder to capture information when an approaching vehicle is at a specific location, a digital camera to store images of oncoming headlamp position (mounting height), two arrays of light sensors to measure the vertical headlamp illumination profile (e.g., angular position of headlamp beam cutoff or maximum luminous intensity), and a color-calibrated illuminance meter at the angular location of an oncoming driver's eyes. From the headlamp mounting height and the vertical cutoff location, an estimate of headlamp aim can be made. The system can be easily deployed within a few minutes and runs on battery power for at least several hours. All data are stored on a laptop computer for subsequent analysis. Data for over 100 vehicles were measured at a roadway intersection location during two nighttime sessions spanning from 8 p.m. to 11 p.m. The present data show that there are weak relationships between headlamp mounting height and estimated illuminances reaching oncoming drivers' eyes, and somewhat stronger relationships between headlamp aim and estimates of oncoming driver eye illuminance. Further, the data provide an estimated distribution of light levels reaching drivers' eyes from oncoming vehicles.

Introduction

Headlamp glare is increasingly recognized by the driving public as an important problem, but there are few data upon which to estimate the light levels reaching drivers' eyes that might produce glare, and even fewer to disentangle the potential reasons for these light levels. Empirically, previous research summarized by the National Highway Traffic Safety Administration (NHTSA, 2007) has identified several factors that are related to the frequency and extent of headlamp glare when driving at night:

- Aim
- Mounting height
- Color
- Size
- Beam pattern
- Condition of headlamps (cleaning and maintenance)

Many of these factors have been studied either alone or in conjunction with another factor (in order to ascertain how interactions between factors might affect headlamp glare). For example, Akashi et al. (2008) demonstrated that increasing the mounting height of an oncoming or following headlamp will increase discomfort glare. However, many of the factors listed above might interact in complex ways in the real world that could affect, for example, the amount of visual disability or discomfort experienced by a driver during a particular encounter with another vehicle. The present study was conducted to assess the potential impact of some of these factors in a real-world setting; not all factors listed above were measured (see Rea [2000] and Bullough et al. [2003] for additional information and background).

The present study was performed with several objectives in mind:

- To design a relatively simple and easy-to-implement measurement system to measure several relevant headlamp and illumination parameters in a real-world setting
- To identify representative ranges of headlamp aim, mounting height, cutoff location, color, and oncoming illuminance under real-world conditions
- To estimate whether, and how much, variations in the factors listed above can influence the amount of light reaching an oncoming driver's eyes in an oncoming vehicle scenario under real-world conditions

In the present study, estimates of the light level reaching the eyes of oncoming drivers are used as a quantity that might be related to disability or discomfort glare, based on previous findings (e.g., Bullough et al., 2003) that these responses are related to the illuminance at drivers' eyes.

Subsequent sections include a description of the measurement system and apparatus and its deployment at an intersection, a summary of the descriptive data recorded by the system during nighttime data collection sessions, and some correlational analyses to estimate the extent to which headlamp parameters such as those listed above can affect glare for an oncoming driver.

Methods

Test Location

An intersection in Watervliet, New York, (16th Street and Broadway) was used as the measurement location following discussion with and permission from the local police department (Figure III-1). This location is a stop-controlled, unsignalized "T" intersection (at its east-most end, 16th Street runs into Broadway), adjacent to a bank and a fast food restaurant. A raised median was present along the east end of 16th street. Traffic on 16th Street traveling east (along the arrow in Figure III-1) had to enter either the left or right turn lane to travel either north or south, respectively, on Broadway. It was decided to measure vehicles in the left-turn lane because observations of traffic patterns at this intersection revealed that there was much less variability in lateral vehicle position in the left-turn lane, owing to the presence of the raised median that prevented drivers from angling their vehicles toward the left. It was also observed that hardly any vehicles actually stopped at the stop line, which was 3 to 4 m behind the most forward edge of the median.

The measurements were made from a position across the intersection on the east side of Broadway (the circled area in Figure III-1). This location was convenient because it had very little pedestrian access; to Broadway's east is an interstate highway enclosed by a chain link fence. It was also useful because the geometry tended to isolate illuminance from the vehicle being measured; headlamp illumination from vehicles in the right-turn lane did not produce measurable illuminance on the apparatus, and most light from any other vehicles behind the one being measured was blocked by the vehicle being measured.

The test location is illuminated by fixed roadway lighting ("cobrahead" style luminaires containing high-pressure sodium lamps mounted on 10 m poles). Thus, illumination from the roadway lighting contributed to all of the illuminance measurements. The vertical illuminance at the test location was measured to be 21 lx.

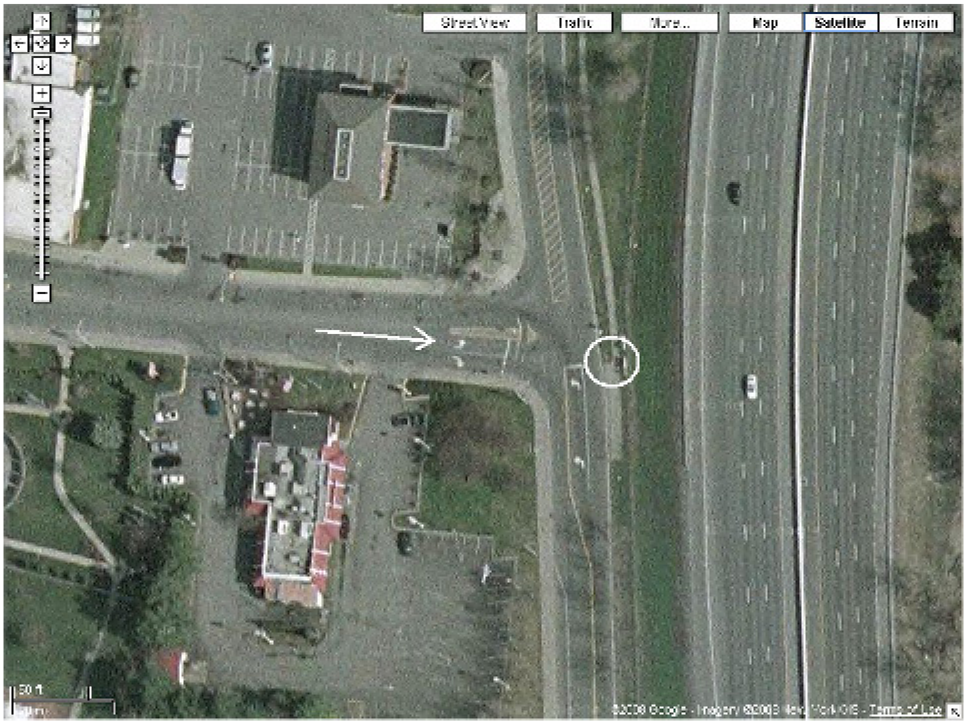


Figure III-1. *Aerial view (courtesy of Google Maps^{TM}) of the test location. The arrow indicates the direction of travel of the vehicles being measured, and the circle indicates the approximate location of the measurement equipment.*

Apparatus

The measurement equipment was located across from the "T" roadway intersection where it was deployed, about 1 m from the roadway. As described above, vehicles in the study moved directly toward the equipment to a stop sign, then made a left turn, as shown in Figure III-2.

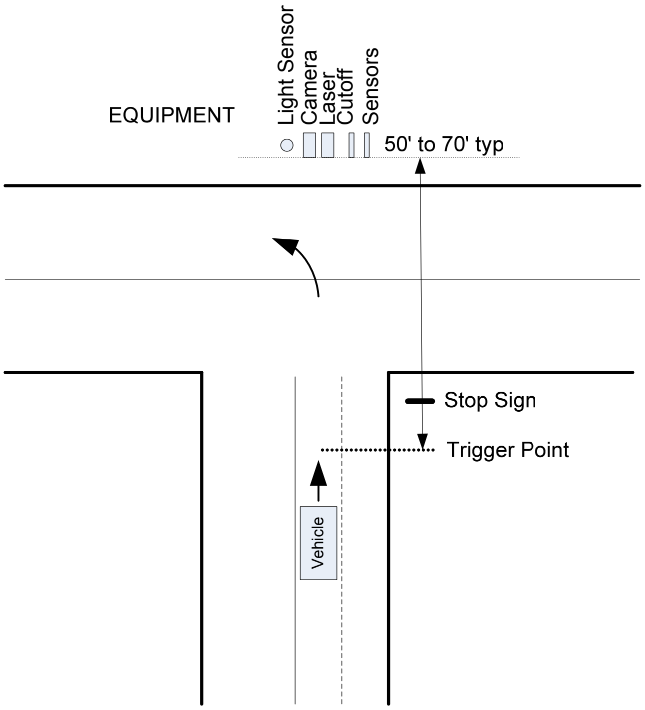


Figure III-2. *Schematic layout of the intersection location.*

Measurements were taken when the vehicle reached a trigger point a few meters ahead of the stop line painted on the roadway surface. Triggering prior to the stop sign minimized downward tilting of the vehicle (and headlamps) due to hard braking. Use of the left lane, rather than the right, minimized angling of the vehicle (and headlamps) toward the direction of the turn because of the presence of the raised median. The distance from the trigger point to the measurement apparatus was dependent on the intersection characteristics, and for the intersection used was 19 m. Figure III-3 shows the layout of the equipment, and Figure III-4 shows a photograph of the system as set up outdoors. All equipment was powered by a 12 V sealed lead acid battery. The height of the equipment was adjusted for the curb height (25 cm) above the roadway surface.

An image processing camera (Basler, scA640-74fm), aimed at the left headlamp (average position), was used to measure headlamp height relative to the road surface. An illuminance meter (Gigahertz-Optik) and detector head measured illuminance, chromaticity coordinates (x,y) and correlated color temperature (CCT) at a specific location. Two vertical linear arrays of analog light sensors measured the vertical distribution of light from the oncoming headlamps at two positions, approximately 2° and 6° to the right of a location directly ahead of the center of the driving lane. Typically, vertical gradient measurements are made at an angular location of 2°, but the additional location was used in the present apparatus in order to provide additional information in case of difficulties with the 2° data, since this was an exploratory study with new measurement techniques. An infrared laser distance measuring system, aimed at the center front of the approaching vehicles, tracked the position of vehicles as they approached the intersection and then started the data acquisitions when they reached the trigger point. An advantage of this type of system is that it permits the system to ignore cross traffic on the street adjacent to the measurement apparatus, since the distances to vehicles traveling on this street would be much shorter than to the vehicles at the stop line of the intersection.

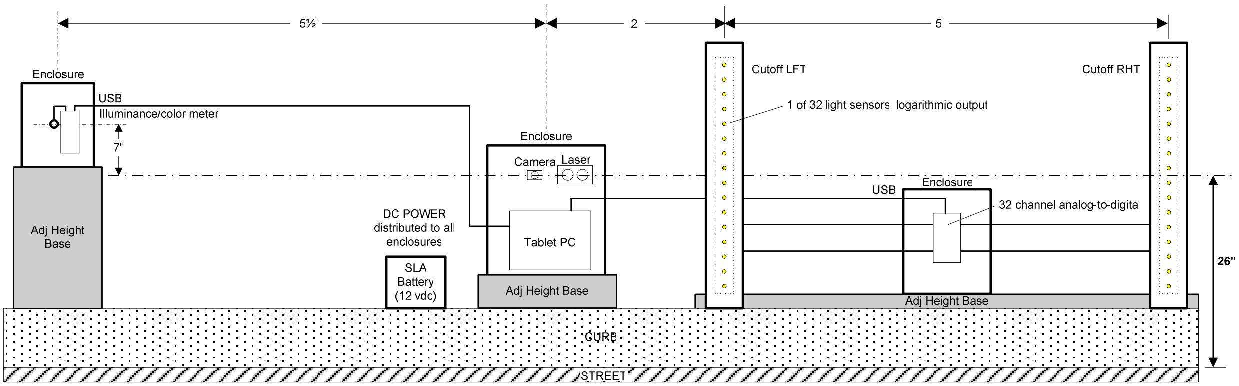


Figure III-3. *Plan view of measurement equipment.*

Laser setup parameters were adjusted to allow distance measurements every three ms, during which time a vehicle traveling at 20 mph (9 m/s) moves 2.5 cm. The laser system met U.S. Food and Drug Administration (FDA) eye safety requirements and is classified as eye safe according to the FDA's (CFR 21) Class I 7-mm limits. A separate red laser beam was turned on briefly during system calibration to adjust the alignment of the infrared measurement laser.

Figure III-4. *Photograph of measurement system.*

The camera employed a 50-mm lens (Fujinon, HF50HA-1B), which provided a 2 m (horizontal) x 1.5 m (vertical) field of view at 15 m and a 3 m x 2 m field of view at 21 m (this corresponds to a angular field of view of about 8º horizontal by 5.5º vertical). Images captured with the camera and lens during daytime conditions were observed to be clear, providing sufficient acuity to estimate headlamp mounting heights. To obtain measurement values in real-world units (cm, not pixels), and to correct for distortions caused by imperfect camera alignment and lens aberrations, a 1.85 m (horizontal) x 1.15 m (vertical) calibration grid, consisting of an 11 row x 18 column matrix of 6.4-cm-diameter white circles on 10-cm centers on a black background, was employed. Prior to collection of data, the grid was positioned at the trigger point, normal to the camera axis, and an image was captured. After on-site data collection, in the laboratory, the calibration was completed by selecting a region of interest (ROI) containing only the calibration grid, performing a calibration using a National Instruments Vision Assistant procedure, then referencing the headlamp images to the ROI and calibration.

The headlamp vertical distribution measurement system consisted of two identical linear arrays of analog photosensors, spaced 1.5 m apart horizontally. Two arrays were used since the headlamps have asymmetrical beams. Each array contained 16 logarithmic-output sensors (OSRAM, SFH5711) with spectral sensitivity close to the photopic spectral sensitivity function, mounted at 5-cm centers, resulting in the capability to measure cutoff within a 76-cm range, with illumination ranging from 3 to 80,000 lx, covering approximately a ±3° spread with a resolution of 0.2°. The sensor voltage signals were input to individual operational amplifiers (Microchip Technology, MCP6G01 Selectable Gain Amplifier) to convert the high impedance output of the sensors, subject to noise pickup, to low impedance output. These low-noise signals were sent in turn to a 32-channel analog-to-digital converter (National Instruments, USB-6218) with 32 analog inputs, 16-bit resolution and a 250 kS/s maximum input rate. Signals were read and processed by the National Instruments LabVIEW software program.

The illuminance meter system included an optical meter (Model HCT-99-D) and a detector head (Model CT-4501-4). Measurements were read via the USB bus and processed by the LabVIEW software program. The color measurement allowed discrimination among headlamp types (i.e., halogen or high-intensity discharge [HID]).

The illuminance meter detector head was positioned so that, from a location at the trigger point distance, it was located along the trajectory of light from the vehicle headlamps to a driver of a hypothetical passenger vehicle in the opposite lane of a two-lane highway, 30 m away (assuming a 1.1 m driver eye height and a 4 m roadway lane width).

Results

This section summarizes the results of initial test runs performed to check the performance of the measurement system, and summarizes the data from the field measurement collections at the intersection measurement location.

Initial Test Runs

Initial data collection trials were performed in the parking lot of the Lighting Research Center in Troy, New York, during a nighttime session with clear weather. Two vehicles that had their headlamp aim and heights measured prior to the trial runs were used (a pickup truck with VOR headlamps and a passenger car with VOL headlamps; both contained halogen lamps and used reflector optics). The measured headlamp height for the truck was 100 cm and for the passenger car was 61 cm. The measured aim of the driver side headlamp on the truck was 0.5^o upward, and the measured aim of the driver side headlamp on the passenger car was 0.2^o downward. A trigger point distance of 20 m was used, and the vertical cutoff at 2^o and the headlamp height were estimated using the procedures described below for the main study results.

Using the measurement apparatus, each vehicle drove toward the trigger point and the apparatus at about 20 mph (9 m/s) and decelerated both gently and rapidly to simulate the maneuvers of traffic at the stop-controlled intersection used in the study. Between three and five repeated measurements for each vehicle were made with different deceleration characteristics. Observations of the beam pattern cutoff during these trials showed little change in pitch (as long as very hard braking [enough to cause skidding] did not occur). The estimated headlamp mounting height for the truck was 99 cm and that of the passenger car was 63 cm. Using the headlamp mounting height and the cutoff height as described below to estimate the headlamp aim for each vehicle, the resulting values for the headlamp aim were 0.3° upward for the truck and 0.3° downward for the passenger car.

The good agreement between the values meant that the system could subsequently be used to gather data on a larger vehicle sample under real-world conditions.

Intersection Test Site Measurements

In total, 139 vehicle data sets were collected over the two nighttime measurement sessions. During both sessions, nights with clear weather without fog or precipitation were selected to minimize variability in measurements. Equipment was placed in the same location during each data collection session. For a few of the data sets, one of the values resulted in highly questionable or obviously incorrect values (e.g., illuminances in the thousands of lx when values were typically between zero and ten lx, or a captured image with no headlamp present). The causes of all of these events could not be ascertained, but some of them were caused by a vehicle position not within the left-turn lane or by pedestrians walking at the same distance as the trigger point (19 m from the measurement apparatus). It is possible that very high illuminances were caused by auxiliary lighting equipment (e.g., fog lamps). There was no evidence found of any equipment-related systematic errors in data collection. Such data were excluded from subsequent analysis, with the result that there were 129 mounting height measurements, 120 cutoff height measurements, and 119 illuminance measurements. Since both mounting height measurements and cutoff height measurements are necessary in order to estimate the headlamp aim, there were 117 total estimated headlamp aim values.

Mounting Height. As described in the previous section, once the apparatus was set in place at the test location (taking into account the curb height above the roadway surface), an image of the calibration grid positioned at the trigger point was captured (e.g., Figure III-5). This image was used to estimate height of the headlamps in the subsequently captured images for each vehicle. For example, Figure III-6 contains a captured headlamp photograph, and by determining the pixel location of the centroid of the headlamp source image, and using the pixel locations of the circles in Figure III-5, the approximate mounting height (to the center of the headlamp) can be estimated.

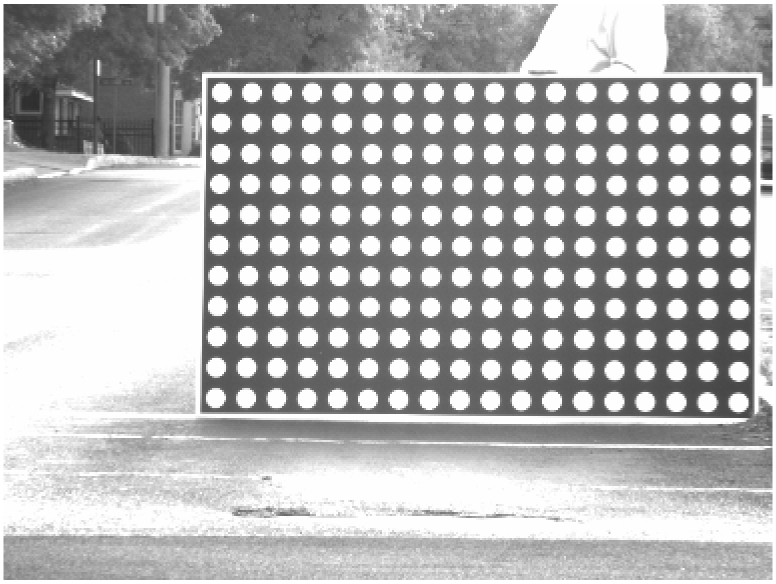


Figure III-5. *Image of calibration grid.*

Figure III-6. *Image of oncoming headlamp.*

A separate calibration image was captured for each data collection session to account for small positional and angular deviations of equipment among sessions. Using the procedure outlined above for each headlamp image, the mounting heights for the 129 values were sorted into 5-cm bins and plotted in the histogram in Figure III-7.

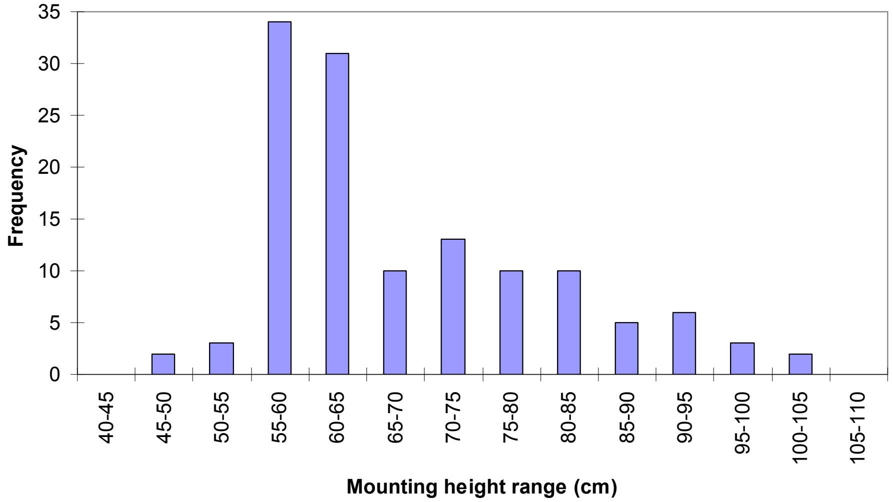


Figure III-7. *Histogram of headlamp mounting heights.*

Just over half of the mounting heights were between 55 and 65 cm. The mean mounting height was 67 cm (standard deviation 13 cm), with a range from 46 to 102 cm. A few were lower than the minimum height (56 cm) permitted by FMVSS 108 requirements. The causes of these deviations are unknown but could be related to under-inflated tires, damaged lighting equipment, or a headlamp image that only showed the lower portion of the headlamp's front lens as illuminated. None of the headlamps that were measured were observed by experimenters to be anything other than headlamps (they were not auxiliary lamps or fog lamps). The types of vehicles (i.e., passenger car versus SUV/truck) were not recorded by experimenters at the scene during data collection so it is not possible to determine the ranges of mounting heights for different vehicle types. All of the measured mounting heights were lower than the maximum allowable height specified by FMVSS 108 requirements (137 cm). There were relatively few headlamps with mounting heights higher than 85 cm, above which glare has been identified (SAE, 2002) as being problematic.

Cutoff Height. To obtain a sense of where the headlamps being measured were directing light forward, the height of the beam pattern's cutoff or gradient was estimated. As described in the previous section of this report, in each vertical array of photosensors, the sensors produced a voltage proportional to the logarithm of illuminance incident on it. The 16 values for each array were treated as follows.

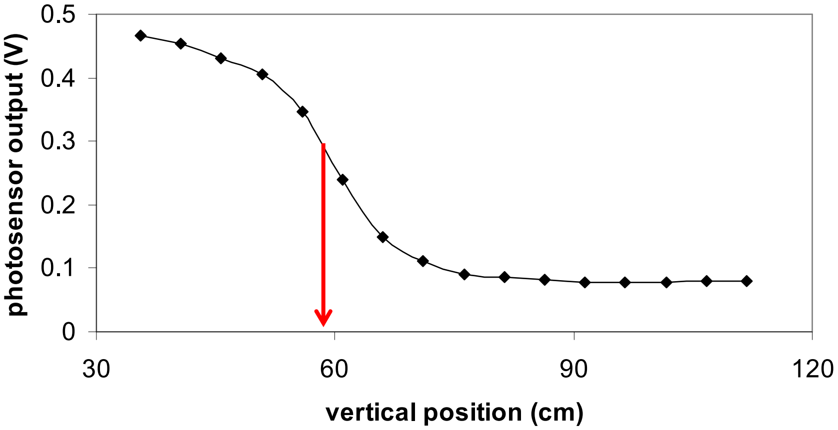


Figure III-8. *Adjusted photosensor output values from the 2°-right vertical array; also shown is the procedure for estimating cutoff height.*

The minimum value at each position was determined, and these values were subtracted from all of the voltage data for each data set. This had the effect of removing the effects of ambient illumination from the roadway lighting. Such subtraction is appropriate because the sensors have an approximately photopic spectral sensitivity and because photometric quantities behave additively (Rea, 2000); that is, contributions from multiple sources can be added individually and the sum will be the same as the total light level from all sources. Figure III-8 shows the output voltage, adjusted in this manner, for the sensor array located 2° to the right of the center of the turn lane for one vehicle. This figure shows the representative shape of the output profile of an array of 16 sensors. From each set of array outputs, the mean of the heights of the two adjacent sensors with the greatest difference was calculated as illustrated in Figure III-8. Since the sensors were spaced 5 cm apart, the resolution of the cutoff height is also 5 cm.

It was a design decision at the outset of the study to utilize two cutoff measurement locations (i.e., 2º, which corresponds to the usual vertical gradient location, and 6º, which was selected as a secondary location in case the 2º data were noisy or difficult to interpret, or in case horizontal mis-aim [which was not measured] was present). Before the study was performed it was unclear whether the usual presence of two headlamps on each vehicle would insert noise into the data at 2º, but as described below, these data did not appear to be excessively noisy.

The vertical arrays only spanned 75 cm in height (from 35 cm to 110 cm above the roadway surface). This was a limitation of the available number of data channels in the apparatus (32, 16 for each array). Therefore, they could not accurately measure low cutoff heights if they were mis-aimed more than 2.5º in the downward direction, nor of high cutoff heights if they were mis-aimed more than 2.5º in the upward direction. For about half of the headlamps, at each array location (2° and 6° to the right), the vertical cutoff was found to have the highest or lowest possible height, indicating that the true cutoff height might be lower than 35 cm or higher than 110 cm. As a conservative estimate of the central distribution of vertical cutoff locations at each location (2° and 6°), Figure III-9 shows histograms of the cutoff locations.

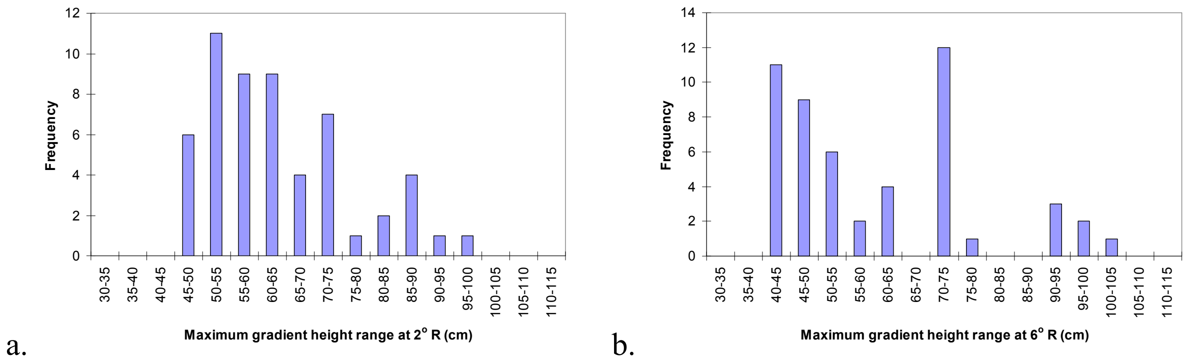


Figure III-9. *Distributions of vertical cutoff heights for positions (a) 2^o and (b) 6^o to the right of center.*

The distributions of the cutoff heights are different for each height. The 2^o-right cutoff heights are distributed similarly to the headlamp mounting heights in Figure III-7, but the 6^o-right cutoff heights are not. However, the mean measured cutoff heights for each angular position (60 cm for 2^o, 62 cm for 6^o) are not substantially different from each other.

Headlamp Aim. Estimates of headlamp aim were made indirectly from the mounting height and cutoff height data based on the finding (Schoettle et al., 2008) that more than 90 percent of all vehicles manufactured since 2004 use headlamps that are aimed using visual/optical alignment (VOA), with about three-quarters of these using the right-hand (passenger) side of the beam pattern for checking alignment. When aimed properly, the right-side cutoff of such headlamps (denoted VOR for visual/optical right-side) is supposed to be positioned at a vertical angle of 0^o. In other words, the right-side cutoff height should be equivalent to the mounting height when these headlamps are correctly aimed. Obviously, many headlamps are not VOR types, but assuming a right-side cutoff of 0^o is probably a reasonable estimate for the majority of beam patterns experienced in the real world (Symtech, 2007), especially given that the median model year in a study of headlamp aim (Chapter IV) was 2003, when it is estimated by interpolation that the majority of headlamps were still VOR types. Also not considered in the present analyses are the possibility of damaged, dirty or foggy headlamp lenses (see Chapter IV), which can affect headlamp distribution. Nonetheless, because of the uncertainties in identifying headlamp type, the aim data from the present study are only estimates. Because the cutoff measurement sampled only one particular location it was not possible to distinguish between VOL and VOR headlamps in the present study.

Thus, knowing the mounting height (h_m), the cutoff height (h_c), and the distance (d) between the measurement location and the headlamps (Figure III-10), it is possible to estimate the aiming angle (θ) as follows:

$$\theta = \arctan([h_c - h_m]/d) \qquad \text{(Eq. 1)}$$

As long as the units of h_m, h_c and d are the same, the equation is dimensionally accurate.

Figure III-11 shows histograms of the headlamp aim estimates for the 2^o and 6^o locations. Both show slight tendencies toward downward aim, consistent with results from an earlier study

(Lighting Research Center, 2005). It is difficult to directly compare the data in Figure III-11 to those from those other studies of headlamp aim, because in the present study, the vertical aim of a headlamp could be influenced by vehicle cargo weight and location (Yokoi et al., 1997), and to a limited extent by acceleration or deceleration of the vehicle (Paetzold and Franke, 2000).

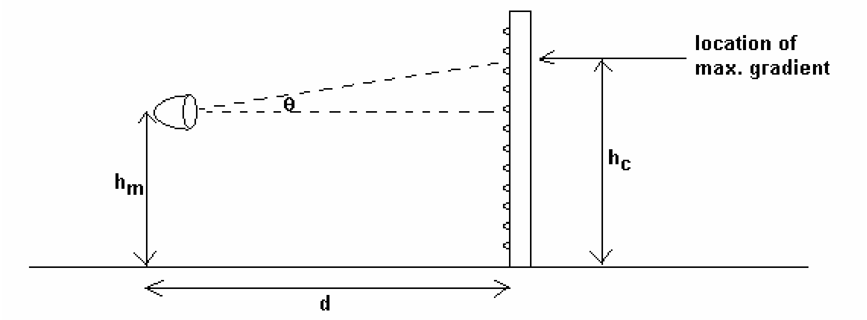
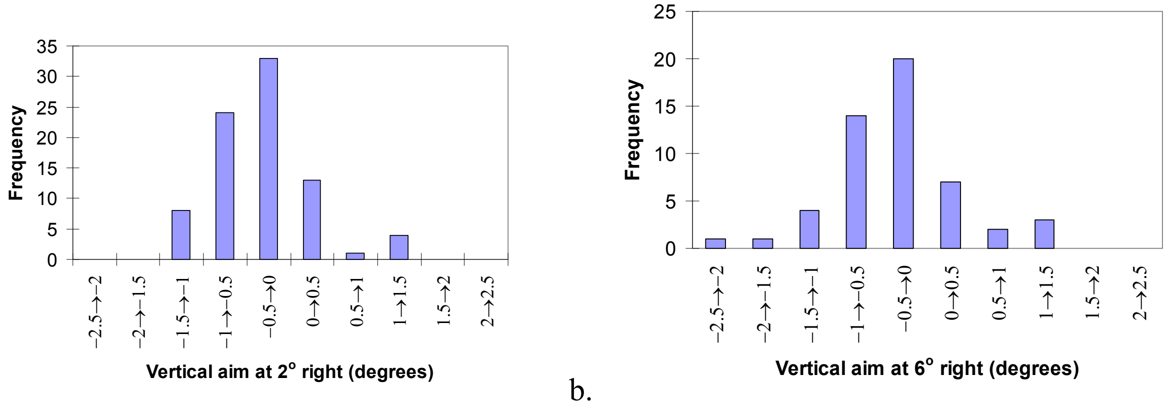


Figure III-10. *Graphical illustration of the estimation method for vertical aim.*



a. b.

Figure III-11. *Histograms of (a) estimated vertical aim at 2°, and (b) estimated vertical aim at 6°.*

Oncoming Driver Eye Illuminance. The illuminance meter used to estimate oncoming driver eye illuminance was located at an angle from a typical headlamp height (66 cm [Schoettle et al., 2002]) such that it would intersect with an oncoming driver's eyes (at a height of 1.1 m [Sivak et al., 1996]) for a driver along a two-lane highway with a lane width of 4 m [Sivak et al., 2004]) located 30 m ahead. (This location corresponds to an angular position of 4º to the left, and 1.2º up from the vehicle headlamps.) Because there was roadway lighting in the area, the minimum illuminance measured during each nighttime session (~21 lx) was subtracted from all of the measured illuminances on each night in order to isolate the contribution from the vehicle headlamps. Subtraction of illuminances was appropriate because illuminances based on the photopic luminous efficiency function are strictly additive (Rea, 2000); that is, the sum of the illuminances from vehicle lighting and from roadway lighting equals the total illuminance combined from these two sources of light.

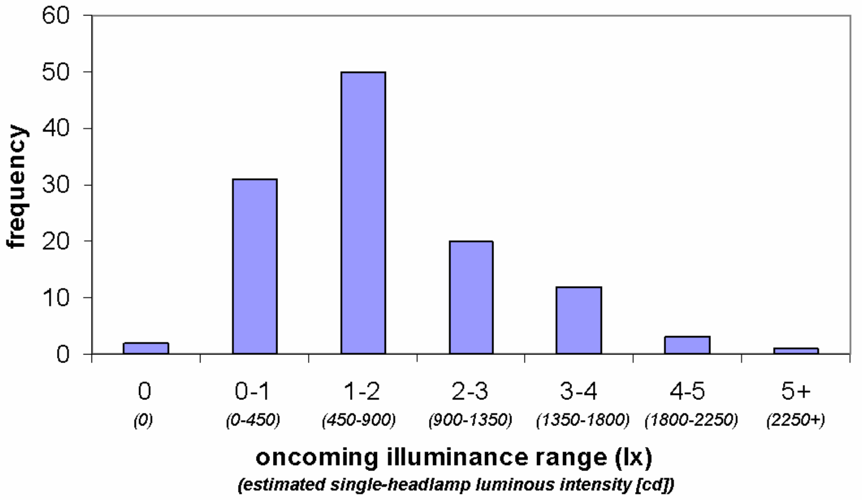


Figure III-12. *Histogram of estimated oncoming eye illuminance values. Corresponding luminous intensities from an estimated headlamp angle of 4° left, 1.2° up are provided in parentheses.*

Since the distance between the illuminance meter and the vehicles being measured was 19 m at the test intersection that was used in the study, the inverse-square law for estimating intensity-illuminance-distance relationships (Rea, 2000) was applied, multiplying the adjusted illuminances by 0.4 ($19^2/30^2$). Figure III-12 shows a histogram of the calculated oncoming driver eye illuminances and the luminous intensities from a single headlamp 30 m away that would produce these illuminances. The mean illuminance was 1.7 lx, with a standard deviation of 1.2 lx, and a range from 0 to 8.5 lx.

Headlamp Color. During both data collection sessions, only three vehicles were observed that appeared to have HID headlamps (out of 139). That fact, combined with the relatively high illuminance contribution to the illuminance meter reading from fixed roadway lighting using high pressure sodium lamps (having a correlated color temperature [CCT; in simple terms, this quantity represents the color of a tungsten filament heated to the temperature given in kelvins] of about 2000 K, corresponding to a yellowish appearance), made it difficult to assess the color characteristics of the headlamps that were measured. Because the roadway lighting had a low CCT and this source was the primary contributor to the measured illuminances, all of the CCTs measured were around 2000-2100 K, with only a very slight but not statistically significant positive correlation between illuminance and CCT, which would be expected since the CCT of halogen headlamps is around 3000-3500 K and that of HID headlamps is around 4000-4500 K, both higher than the CCT of high pressure sodium lighting, so that the higher illuminances should be associated with higher CCTs. The illumination from the fixed roadway lighting system dominated the color measurements; besides, there were very few HID headlamps observed by experimenters during data collection.

Fortunately, the relatively large contribution from the roadway lighting did not impact the utility of the measurements because light measurements from different sources are additive, and the ambient light level can be subtracted directly from the measured values.

Further Analyses

In the present section, several analyses are performed to determine whether there are systematic relationships among the different parameters that were measured.

Does Mounting Height Influence Oncoming Illuminance?

As described in NHTSA's (2007) report to Congress on nighttime glare and driving performance, factors such as the mounting height and aim of headlamps are likely to affect the amount of light reaching drivers' eyes that might produce glare, but it has been difficult to assess the relative contributions of these parameters since they have not often been measured simultaneously in the field along with the illuminance at oncoming drivers' eyes.

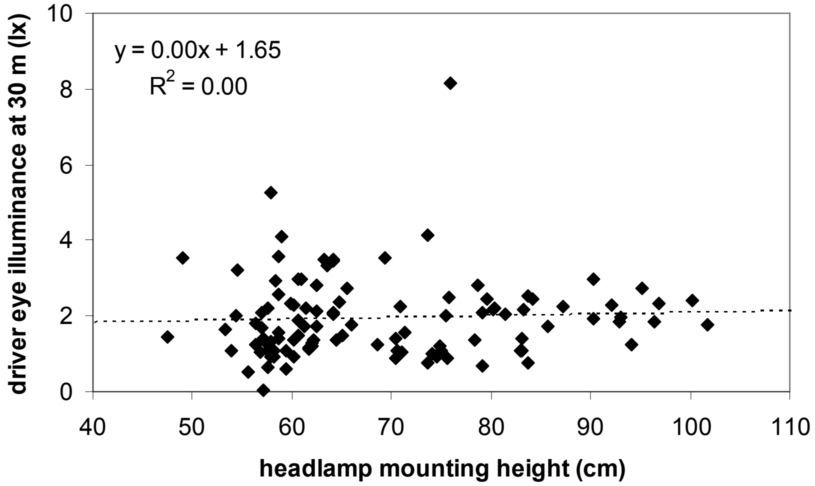
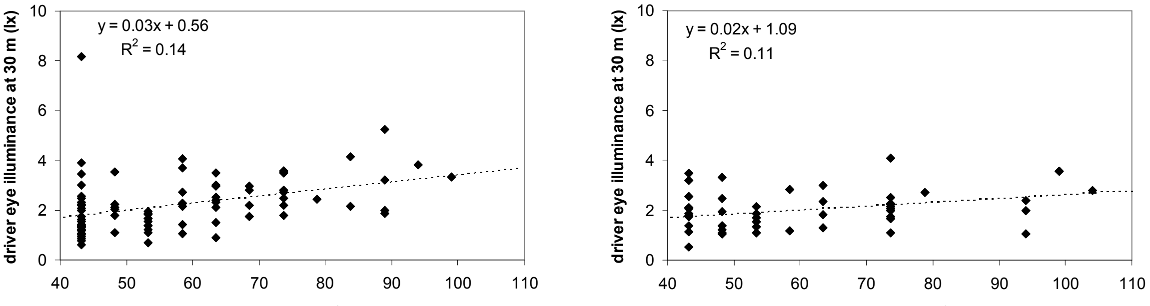


Figure III-13. *Relationship between mounting height and oncoming driver eye illuminance values in the present study.*

Figure III-13 shows the relationship between mounting height and estimated driver eye illuminances measured in the present study. Caution should be used in interpreting this relationship because the distribution of headlamp mounting heights was not uniform in the sample measured; there were more vehicles with lower headlamp mounting heights (i.e., passenger cars) than with higher headlamp mounting heights (i.e., trucks and SUVs). Nonetheless, the figure shows little apparent relationship between these two factors for the sample of vehicles measured (for example, there is no obvious relationship between eye illuminance and mounting height for mounting heights between about 50 and 70 cm, nor between about 75 and 100 cm). Why then did Akashi et al. (2008) find that there was a relationship between mounting height and both disability and discomfort glare, which are strongly dependent upon illuminance at the eye? Important to recall is that in the present study, glare was not measured directly. Rather, the illuminance that might be present at an oncoming driver's eyes is measured as a parameter that logically is related to glare (Bullough et al., 2003), but is not equivalent to glare. One factor to begin to explain the apparent contradiction between the present data and the results of Akashi et al. (2008) might be the fact that Akashi et al. used the same headlamp set and adjusted it to various heights. Since all vehicles have different headlamp beam pattern designs (but conform to U.S. Federal Motor Vehicle Safety Standard No. 108), it is not known whether or how headlamps for vehicles with higher mounting heights in the present sample are different than those for low mounting heights. Further, Akashi studied a wide range of mounting heights, up to 120 cm, and as described above, there were relatively few high mounting heights measured in the present study sample.

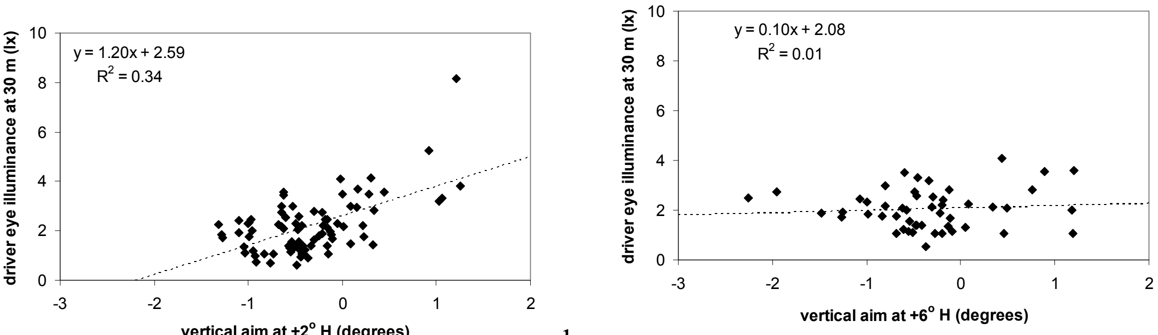


a. b.

Figure III-14. *Relationships between cutoff height and oncoming eye illuminance (a) for 2° and (b) for 6°.*

Does Cutoff Height Influence Oncoming Illuminance?

Figure III-14 shows the relationships between the heights of the measured cutoff locations (at 2° and 6° to the right of center) and the oncoming eye illuminances. Both graphs in Figure III-14 show weak but statistically significant ($p<0.05$) positive correlations between each pair of variable values. Statistical significance in this case means only that it is likely that the correlation coefficient is greater than zero, but does not suggest the correlation has a large practical importance; indeed, the slopes of the functions in Figure III-14 are quite low.



a. b.

Figure III-14. *Relationships between estimated headlamp aim and oncoming illuminance (a) for 2° and (b) for 6°.*

Does Headlamp Aim Influence Oncoming Illuminance?

The height of the cutoff, which in principle should be dependent upon the mounting height and upon the headlamp aim, was reliably correlated with oncoming eye illuminance for the vehicle sample measured. However, the mounting height had no apparent relationship with oncoming illuminance for the vehicle sample measured. It seems logical, then, that headlamp aim should be related to oncoming illuminance, and Figure III-15 shows these relationships when headlamp aim is estimated using the 2° and 6° cutoff heights. There is a moderate relationship between aim and oncoming illuminance for the 2° location, but virtually none for the 6° location. This suggests that using the 2° location is a more reliable estimate of cutoff height than using the 6° location, which is also consistent with the more sporadic distribution of cutoff heights at 6° shown in Figure III-9.

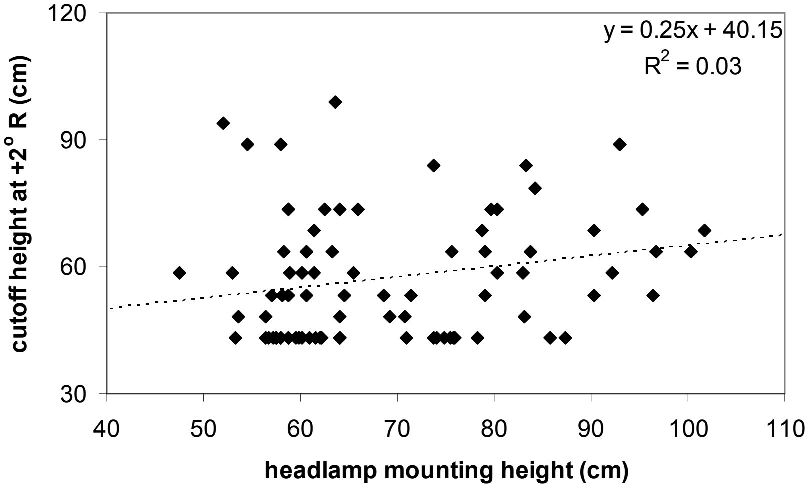


Figure III-15. *Relationship between mounting height and cutoff height at 2°.*

Thus, the mounting height appears to have little influence on either oncoming illuminance (Figure III-13) or on the height of the cutoff (Figure III-15, for the 2° cutoff), based on the vehicles in the present sample (although the limited number of higher-mounted headlamps in the sample limit ability to generalize this finding to the vehicle population at large).

Preliminary Conclusions

As described above, the present study was performed with several objectives in mind:

- To design a relatively simple and easy-to-implement measurement system to measure relevant headlamp and illumination parameters in a real-world setting
- To identify representative ranges of headlamp aim, mounting height, cutoff location, color and oncoming illuminance under real-world conditions
- To estimate whether, and how much, the factors listed above have influence on the amount of light reaching an oncoming driver's eyes in a vehicle meeting scenario

Regarding the first objective, the system described in this report appears to provide an efficient tool for measuring meaningful samples of vehicles in the real world to assess impacts of headlamp parameters on an important quantity that can be related to glare. The system could be implemented at a number of locations such as the intersection used in the present study, curves, in parking lots and garages and in drive-thru installations. Measurements using the cutoff arrays and illuminance sensor with no vehicles present (as a baseline) would perhaps be a useful technique to ensure that ambient sources of light are properly accounted for in the data, although the subtraction technique used in the present study may provide a useful backup method if baseline measurements are not practical.

An important caveat that should be considered is that a preponderance of headlamp mounting heights in the present vehicle sample were less than 85 cm, with relatively fewer headlamps mounted higher than 85 cm, a height above which glare has been recognized as a problem (SAE, 2002). Thus, any findings regarding mounting heights above 85 cm should be considered to be tentative.

An improvement to the apparatus in terms of the cutoff height measurement in subsequent measurements might be to measure the 2º cutoff only and use the 32 sensor arrays to cover a winder range of heights. This would permit both closer than 5 cm spacing and a greater range while still using the limit of 32 sensors in the apparatus.

Regarding the second objective, the data in Figures III-7 through III-12 provide initial estimates for real-world values of several important glare-related parameters (e.g., headlamp mounting height, aim, oncoming driver eye illuminance). The measurement of headlamp color was not successful in the present study, primarily because of the large influence of roadway lighting. Although post-data-collection methods were able to be applied to the illuminance and cutoff sensor data to isolate headlamp illumination from roadway lighting, such methods were not possible using the color data that were recorded. Obviously, performing such a study in a rural, rather than the present urban, location might dramatically change the picture. It would probably also be helpful to use a baffle or shield near the illuminance meter sensor location to block as much illumination as possible from overhead roadway lighting to minimize its influence.

The findings from the present study must be tempered by the fact that relatively few vehicles with high mounting heights were found in the sample of vehicles that was measured. Although the present data do not suggest a strong role of mounting height on the illuminance toward an oncoming driver's eyes, other evidence (Akashi et al., 2008; SAE, 2002) suggests that high mounting heights, particularly above 85 cm, can be problematic at least in some situations.

The present study did not yield a sample of vehicles using HID headlamps that could be studied in any systematic manner. Only three vehicles with HID headlamps were observed. Using a rural location or baffling the illuminance sensor to minimize fixed roadway lighting would help differentiate halogen from HID headlamps, but a larger sample of vehicles (~1000) would certainly be necessary to obtain even a small sample of HID headlamp measurements.

Regarding the final objective, the results of the study demonstrated that, for the sample of vehicles measured, headlamp aim appeared to have the strongest influence on the amount of light that might reach an oncoming driver's eyes of all of the variables studied. As mentioned earlier, mounting height has been shown in other studies to affect headlamp glare (Akashi et al., 2008; SAE, 2002), which is influenced by the amount of light at a driver's eyes, but the data from the present vehicle sample (albeit containing mainly low mounting heights) yielded very weak relationships between mounting height and oncoming illuminance.

In the present study, headlamp aim is related to the orientation of the headlamps within the vehicle and to the pitch of the vehicle based on acceleration parameters and the weight and distribution of cargo, neither of which were assessed in the present study. The location used was a flat intersection where the majority of vehicles decelerated smoothly without much observed change in vehicle pitch. (It was not possible to measure stopped vehicles because not all vehicles came to a stop and because of the variable distance at which stopping, when it did occur, happened.) Still, the general consistency between the headlamp aim results and those of earlier studies suggest that these factors might not have had strong influence on aim.

The results suggest that if vehicle headlamps were more consistently aimed, that the amount of light reaching oncoming drivers' eyes would be more consistent. However, because the average headlamp aim was slightly downward (as measured in the present study and in Chapter IV), more consistent aim might mean higher aim in general. This might have the effect of *increasing* oncoming driver eye illuminance and therefore potentially increasing discomfort glare to drivers (NHTSA, 2007). On the other hand, downward aim has been demonstrated in previous analytical studies to reduce forward visibility. In such cases, more consistently correct headlamp aim should improve driver visibility. Whether improving one's headlamp aim might actually help in increasing the resistance of a driver to discomfort glare is not well understood. The real-world results of the present study can be used to select representative parameter values (e.g., mounting heights, aim, estimated oncoming illuminances) in subsequent research from NHTSA and other organizations.

IV. HEADLAMP AIM SURVEY

Summary

Using a modified portable headlamp aiming device, the vertical aim of low-beam headlamps was measured for more than 100 in-use vehicles and for 20 new vehicles to determine the likelihood and extent of mis-aim. A wide range of mis-aim was found for both the in-use and new vehicle samples. On average, headlamps for in-use vehicles were aimed slightly downward, and for new vehicles were aimed close to the nominally correct alignment. About 62% of in-use vehicles have at least one headlamp aimed outside the tolerances allowed by the standards of the Society of Automotive Engineers, consistent with the results of previous studies. About 30% of the new vehicles measured had at least one headlamp mis-aimed. There did not appear to be any statistically reliable relationships between mis-aim and vehicle age, vehicle type (passenger cars versus trucks, sports-utility vehicles [SUVs] and minivans), headlamp optical systems (reflector versus projector headlamps) nor headlamp source (halogen versus high intensity discharge [HID]). Based on the samples measured, it would be relatively common to find headlamps that produce high light levels above the horizontal plane. Automatic headlamp leveling systems if they can maintain calibration, and to a lesser extent, proper aim of headlamps when a new vehicle is sold, might reduce the likelihood of headlamp mis-aim on vehicles in the United States, but further information regarding the causes of headlamp mis-aim is probably needed before such systems could be implemented.

Introduction

In its report to Congress entitled *Nighttime Glare and Driving Performance*, NHTSA (2007) identified several characteristics of headlamps and vehicles that contribute to headlamp glare as defined by reduced visibility and by increased visual discomfort: mis-aim, mounting height, beam distribution, color, optical design, and maintenance. The present chapter summarizes research activities undertaken to understand the first issue and its possible interactions with the others listed above.

For the purpose of the present study, mis-aim is defined as a headlamp whose vertical orientation is 0.76^{o} or more from a horizontal through the center of the headlamp, based on standards published by the Society of Automotive Engineers (2002). The method for determining whether and how much a headlamp is mis-aimed differs for different types of headlamps. In previous decades, many headlamps were aimed mechanically through the alignment of protrusions in the headlamp lens material that could be used to set the proper aim level.

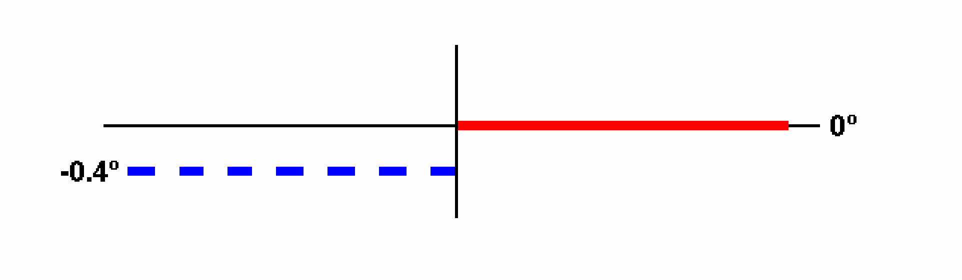


Figure IV-1. *Reference lines for visual/optical alignment headlamps. The thick solid line represents the position of the right-side cutoff for VOR headlamps on a vertical screen located ahead of the headlamp (with the headlamp position corresponding to the intersection of the thin black lines); the thick dashed line represents the position of the left-side cutoff for VOL headlamps.*

More recently, visual/optical alignment headlamps have become more common on vehicles so that these are now found on more than 90 percent of vehicles in the U.S. market (Schoettle et al., 2008). Of this latter type, about three-quarters use the position of the right-hand (passenger) side of the beam distribution's cutoff (these are denoted VOR for visual/optical right-side), when the headlamp is projected onto a vertical screen 7.6 m ahead, to determine the aim status, and the remaining use the position of the left-hand (driver) side cutoff (these are denoted VOL for visual/optical left-side). For a VOR headlamp, the right-side cutoff is supposed to be located at a vertical position that corresponds to a 0^{o} elevation from the mounting height of the headlamp; for a VOL headlamp, the left-side cutoff is supposed to be located at a vertical position that corresponds to a -0.4^{o} elevation (0.4^{o} down) from the mounting height (Figure IV-1).

There are not any Federal standards regulating the aim status of headlamps on vehicles in the United States, although some States require proper headlamp aim as part of annual safety inspections. The number of States checking headlamp aim has decreased in recent years (Texas Department of Public Safety, 2000). Previous studies have been conducted to assess the proportion and degree of mis-aimed headlamps on vehicles. Copenhaver and Jones (1992) measured vehicles from two States, one that included headlamp aim as part of the safety inspection (Virginia), and one that did not (Maryland). About half of the vehicles from both States had at least one headlamp mis-aimed, with a slightly higher likelihood of mis-aim in Maryland than in Virginia. A survey of vehicles a decade later in New York State (Lighting Research Center, 2005) found that more than 60 percent of vehicles in that study had at least one mis-aimed headlamp.

Headlamp aim can be affected by a number of factors (Olson and Mortimer, 1973) including duration of service, aging of the lamp and optical system, vehicle body condition, vehicle loading condition, and tire condition. Outside of the issue of vehicle loading, which has been studied in some detail by Yokoi et al. (1997), the influence of these factors, if any, on aim of present-day headlamps is largely unknown. Presumably, new vehicles sold at dealerships are equipped with properly aimed headlamps, but as pointed out in NHTSA's (2007) report to Congress on headlamp glare, few data exist to determine the extent to which this inference might be correct.

The objective of the present study was to begin to identify answers to the following questions:

- Can a portable headlamp aim measurement device be used to reliably measure aim characteristics of headlamps?
- How many headlamps are mis-aimed and to what extent are they mis-aimed on in-use vehicles?
- What is the distribution of headlamp aim for new vehicles?
- Are there any systematic relationships between mis-aim and other headlamp characteristics?
- Are there any systematic relationships between mis-aim and vehicle characteristics?

The subsequent sections of this report describe the development of a methodology for measuring headlamp aim in the field, and summarize the resulting measurements.

Methods

Testing Apparatus

The device used to characterize headlamp aim was a modified version of a commercially available portable headlamp aiming device (CVA 3 EZ, Symtech Corportation; Figure IV-2). The literature that accompanies this device states that the device can be used to check the aim of visual/optical alignment headlamps. The main components of this device are the optical head, the floor slope laser, and the base with a floor-slope-compensating axle.

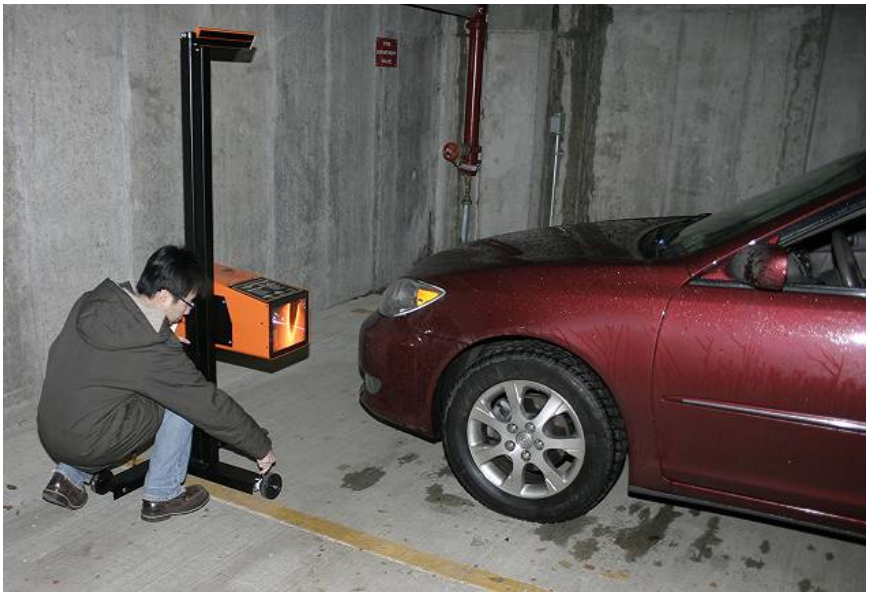


Figure IV-2. *Researcher adjusting the position and orientation of the headlamp aim measurement device.*

The device contains a lens and projection screen with a calibration grid to assist in headlamp aiming. The calibration grid is based on SAE Standard J599. The modification performed consisted of creating a printed screen with a grid that had been optimized for measuring beam position to take the place of the original screen which was optimized for setting headlamp aim. The scale and spacing of the markings were not adjusted.

The replacement screen was designed using computer aided design (CAD) software, precisely aligned (to preserve the device's factory calibration), and secured over the original screen with adhesive. The white surface of the replacement screen allowed the researchers to photograph the beam patterns and analyze them for aim in the laboratory.

Validation of Device Measurements

To ensure that the modified headlamp aiming device would be suitable for measurement of headlamp aim in the field, measurements of two headlamps (a halogen projector VOR headlamp, and a halogen reflector VOL headlamp) were made using the device and using the standard (SAE, 2002) method with a vertical screen located 7.6 m ahead of the headlamps. All measurements were made in a laboratory at the Lighting Research Center. In each case, the proper orientations of each headlamp and of the measurement equipment were checked using laser leveling equipment.

Each headlamp was aimed, using the screen method (SAE, 2002), to vertical positions of 1° up, 0°, and 1° down, and the vertical aim of each headlamp in each vertical position was measured using the portable device, aligned by positioning the device 30 cm (12 in.) in front of the headlamp. The position of the cutoff imaged through the lens of the device onto the calibration grid was noted. In each case, the location of the cutoff using the device matched that on the vertical screen.

Conventional aim methods (SAE, 2002) use a distance of 7.6 m, which generally ensures that the assumptions for far-field photometry (Rea, 2000) are met. The modified headlamp aiming device used in the present study uses near-field measurement conditions (30 cm from the headlamp). Such conditions could lead to errors in estimates of luminous intensity values. Although the purpose of the measurements of aim was not to characterize the luminous intensity of the headlamps, the sensitivity of the aim measurement accuracy was checked by adjusting the distance between the headlamp and the measurement device aperture from 15 cm to 45 cm (the documentation for the aim measurement device provided by the manufacturer states that the distance between the headlamp and device aperture should be 30 cm ± 15 cm). None of the headlamp aim measurements were changed for any of the distances used, supporting the suitability of the portable measurement device for measurement of headlamp aim. For the first dozen of the subsequent measurements, the resulting aim measurements at 30 cm were compared visually to aim measurements with the device located 15 and 45 cm away from the headlamp. None of the headlamp beam cutoff locations differed visually for different distances.

Experimental Procedure

The experiment was conducted using 20 new vehicles on site at a dealership as well as an additional 102 privately-owned in-use vehicles at the Rensselaer student auto shop and the parking lot of a retail establishment. Several dozen privately owned cars were tested at the Rensselaer student auto shop on a volunteer basis; however, due to a lack of volunteers, the quantity of cars sampled at this location was small. Because of the low initial volunteer turn out, data were collected in the parking lot of a local retail business and $5 gift vouchers were distributed to volunteers who participated in the study. Both new cars and in-use vehicles were tested using the same testing device and testing procedure, described below.

Cars were first directed, one at a time, to the testing area. The testing area was selected to be as flat a surface as possible (as determined by the experimenter) where the car could be parked for all measurements. Participants owning a currently registered car were asked to complete a consent form and a driver survey while the car was being tested. No consent form or driver surveys were completed for the new cars. In addition to the driver survey, a member of the experimental team gathered information about the vehicle being tested.

After the vehicular information was gathered, the testing device was aligned so that the optical head was at the same slope as the car. This was done by first positioning the testing device's optical head approximately 30 cm (12 in.) in front of the headlamp. The device was then rolled toward one side of the car. The floor slope laser was activated and a measurement at the center point of the front wheel from the ground to the floor slope laser mark. The next measurement was made at the center point of the back wheel from the ground to the laser mark. The two measurements from the front and back wheel were compared. If the measurements are different then the floor slope axle on the base was adjusted so that the measurements taken at the front and back wheel were equal. Equality of these measurements indicated that optical head had the same slope as the car. The device was then moved back in front of the headlamp.

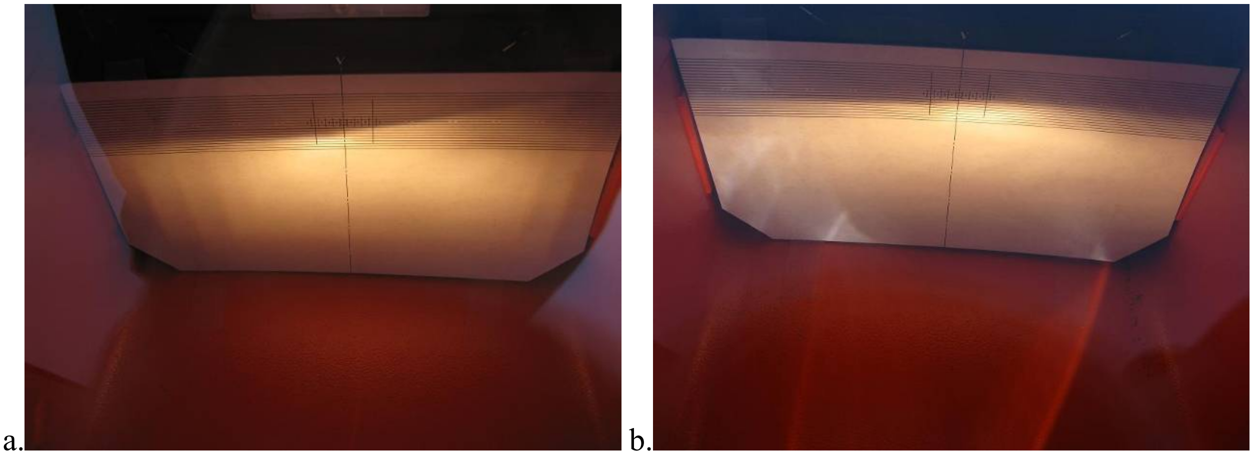

a. b.

Figure IV-3. *a: Image of the calibration grid when illuminated by a VOL headlamp; b: Image of the calibration grid when illuminated by a VOR headlamp.*

A digital camera was used to take a picture of the vehicle's license plate (so that the data could be linked to each vehicle individually); however for new cars the vehicle identification number (VIN) was photographed instead. Next, a photograph of the headlamp was taken to document its physical condition. At this point the headlamps of the car were turned on and the optical head was positioned in front of the headlamp so that the headlamp's beam pattern was projected onto the scale inside the optical head. Next, a photograph was taken of the headlamp beam pattern projected on the scale in the optical head (Figure IV-3). Privately owned cars tested in the Rensselaer auto shop were tested indoors. Privately owned cars tested in the retail parking lot, as well as all new cars tested at the dealership's on-site storage lot, were tested outside. The cars that were tested outdoors required a sunshade to reduce the ambient light over the measuring device while photographing the headlamp beam projecting on the scale. The measuring device was then moved to the opposite headlight and the measurement procedure was repeated starting with the adjustment of the optical head for the slope of the ground. The entire measurement process took about 15 minutes per vehicle.

Post-Analysis

The final step of the measurement procedure was determining and recording the aim of the headlamp. This was done by reviewing the photographs recorded in the field. The part of the headlamp beam that is of concern is any part of the beam that is above the horizontal aim line. Therefore, the aim of the beam was determined by looking for the beam pattern's cutoff at the top of the beam pattern. The beam was projected onto the scale and the location of the cutoff was recorded to a spreadsheet. The scale marks were located on the grid such that the distance between each scale mark would correspond to 1 in. of height if the headlamp were projected onto a vertical screen 7.6 m (25 ft) ahead. Each recorded value corresponds to the number of scale marks above or below the horizontal line the cut off projects. For example, if the cut off was 3 scale marks up, a value of 3 was recorded; if the cutoff was 2 scale marks below horizontal, a value of -2 was recorded. The recorded number was subsequently converted to a measurement of degrees by applying a factor of 0.19^{o}/in.

Results

The results of the measurements are discussed in the context of the research questions identified above:

Vehicle Demographics: In-Use Sample

During data collection, the experimenters recorded information such as the vehicle age, vehicle type (passenger car or light truck/sports utility vehicle/minivan), headlamp optics type (reflector or projector), light source (halogen or high intensity discharge [HID]), alignment type (VOL or VOR).

The experimenters recorded whether each headlamp was a VOL or VOR type by inspecting the marks on each headlamp. When no such marks were present (for eight vehicles), the headlamp was assumed to be VOR type for the purpose of analysis, unless it had a beam pattern such as that illustrated in Figure IV-3a (for three of the eight vehicles), where the right-side cutoff angles upward from the central part of the beam pattern, rather than exhibiting a horizontal cutoff pattern. These latter headlamps were treated as VOL types for subsequent analysis. Experimenters also recorded the condition of each headlamp (whether the headlamps were dirty, contained condensation, or were damaged through abrasion or oxidation of the lens material).

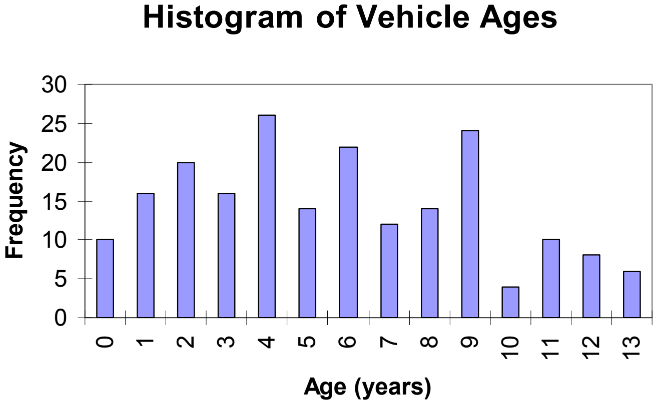


Figure IV-4. *Distribution of ages for the in-use vehicles in the present study.*

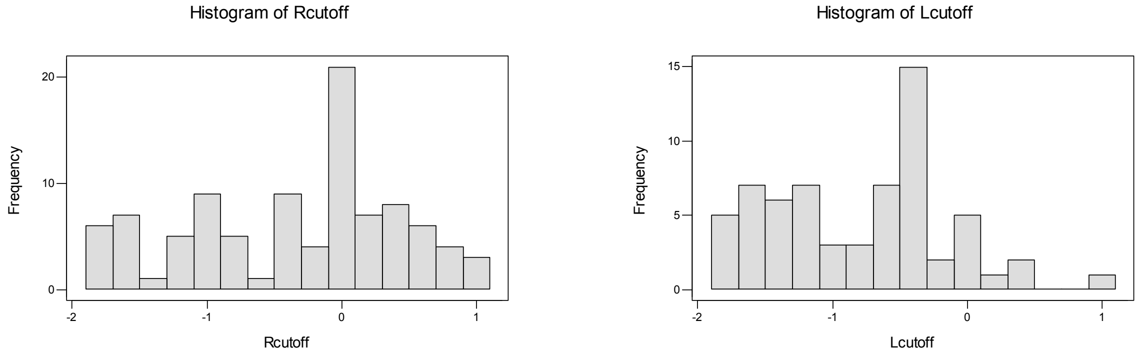
Figure IV-4 shows the distribution of in-use vehicle ages in the study, which ranged from zero (2008 model year) to 13 (1995 model year) years old. Table IV-1 lists the remaining demographic information for the vehicles in the in-use sample.

Vehicle/Headlamp Characteristic	**Percentage of Sample**
Vehicle type	65% passenger cars, 35% other
Headlamp optics	84% reflector, 16% projector
Light source	96% halogen, 4% HID
Alignment type	61% VOR, 39% VOL
Headlamp cleanliness	78% clean, 22% dirty
Headlamp condensation	88% no condensation, 12% condensation
Headlamp damage	80% no damage, 20% damage present

Table IV-1. *Demographic characteristics of vehicles and headlamps in the in-use vehicle sample.*

Summary of Headlamp Aim Distribution: In-Use Sample

Figure IV-5 shows the distribution of right-side cutoff locations for the VOR headlamps, and the distribution of left-side cutoff locations for the VOL headlamps. As the data in this figure suggest, the mode for each type of headlamp alignment was the proper angle associated with each type (0^o for VOR headlamps and $–0.4^o$ for VOL headlamps), although the mean aim value for each type was low: -0.3^o for VOR headlamps and $–0.8^o$ for VOL headlamps.



a. b.

Figure IV-5. *Distribution of relevant cutoff locations for (a) VOR headlamps and (b) VOL headlamps from the in-use sample.*

Using the criterion value of 0.76° as the maximum allowable tolerance from the proper aim for the relevant cutoff, 47 percent of the vehicles with VOR headlamps had both headlamps within the allowable tolerance, and 27 percent of the vehicles with VOL headlamps had both headlamps within the allowable tolerance. Overall, 38 percent of all of the vehicles measured had both headlamps within the aim tolerance, meaning 62 percent had at least one headlamp mis-aimed. In general, this is consistent with the results of a previous study (Lighting Research Center, 2005), which found that about two-thirds of the vehicles measured had at least one headlamp mis-aimed.

Vehicle Demographics: New Sample

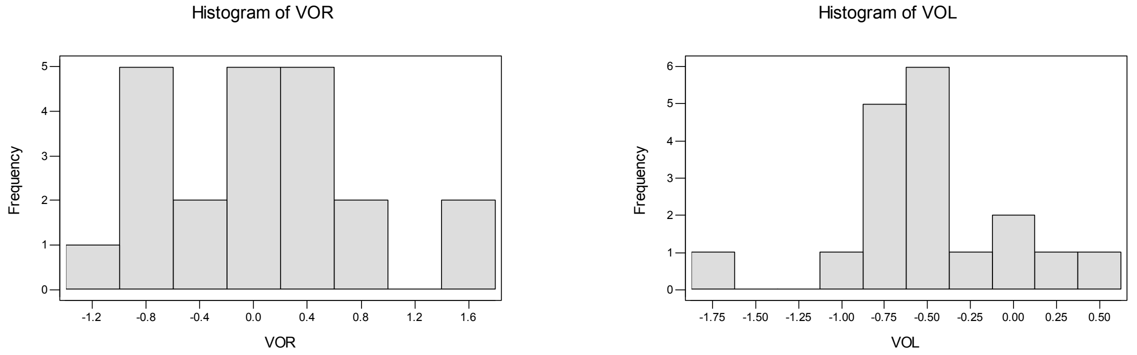
Table IV-2 summarizes the demographic characteristics of the vehicles and headlamps in the new sample. Because all of the vehicles in this sample were new, neither age, dirt, condensation, nor damage were relevant characteristics.

Vehicle/Headlamp Characteristic	Percentage of Sample
Vehicle type	95% passenger cars, 5% other
Headlamp optics	40% reflector, 60% projector
Light source	60% halogen, 40% HID
Alignment type	55% VOR, 45% VOL

Table IV-2. *Demographic characteristics of vehicles and headlamps in the in-use vehicle sample.*

Summary of Headlamp Aim Distribution: New Sample

Figure IV-6 shows the distribution of cutoff locations for the VOR and VOL headlamps in the new vehicle sample. The mean cutoff location for the VOR headlamps was 0.1°, and the mean cutoff location for the VOL headlamps was –0.5°. Thirty-six percent of the VOR vehicles and 22 percent of the VOL vehicles had at least one headlamp mis-aimed by more than 0.76°. Overall, 70 percent of the new vehicles in the sample had both headlamps aimed within the SAE's (2002) allowable tolerance. Causes for mis-aimed headlamps cannot be ascertained from the sample.



a. b.

Figure IV-6. *Distribution of relevant cutoff locations for (a) VOR headlamps and (b) VOL headlamps from the new vehicle sample.*

Discussion

The results of the present study are discussed in light of the research questions described earlier:

- Can a portable headlamp aim measurement device be used to reliably measure aim characteristics of headlamps?
- How many headlamps are mis-aimed and to what extent are they mis-aimed on in-use vehicles?
- What is the distribution of headlamp aim for new vehicles?
- Are there any systematic relationships between mis-aim and other headlamp characteristics?
- Are there any systematic relationships between mis-aim and vehicle characteristics?

Regarding the first question, the validation exercise demonstrated that cutoff locations assessed using the modified headlamp alignment device matched those projected onto a vertical screen located 7.6 m in front of headlamps aimed to an arbitrary angle.

Regarding the second and third questions, the results of the in-use vehicle study shows that about 60 percent of in-use vehicles in the sample measured had at least one headlamp mis-aimed, and 30 percent of the new vehicles measured had at least one mis-aimed headlamp. There was a broad distribution of mis-aim both upward and downward for both in-use and new vehicles. The mean mis-aim for the in-use vehicle sample was about half a degree downward, and for the new vehicle sample was close to zero degrees.

To address the last two questions, analyses of variance (ANOVAs) were conducted on the vertical cutoff values for each type of headlamp alignment (VOR and VOL), with vehicle age, vehicle type (i.e., passenger cars versus SUVs/trucks), headlamp optics and headlamp source type as independent variables for the in-use sample. (No VOR headlamps contained HID lamps, so this variable was not included for the VOR headlamp analysis.) None of the independent variables had statistically reliable main effects on the measured cutoff position ($p>0.05$).

While not directly related to aim status, regression analyses were performed to determine, if as might be expected, the ages of vehicles in the in-use sample were related to the likelihood that the headlamps were dirty, contained condensation, or were damaged. Statistically reliable ($p<0.05$) positive correlations were found between vehicle age and the probability of condensation and between vehicle age and the probability of damaged headlamps. Both of these factors, obviously, can affect the light distribution produced by the headlamps, but might often go unrecognized by drivers.

The size of the new vehicle sample (20 vehicles) is too small to conduct reliable statistical analyses to test associations between vehicle/headlamp characteristics and aim status. Nonetheless, this sample does provide suggestive evidence that while the mean aim status of headlamps on new vehicles might be close to nominally correct, there can be wide variability in mis-aim of headlamps on new vehicles, which might be passed on to owners of these vehicles when they are purchased.

Because the present study measured only the location of the horizontal cutoff of vehicles in the two samples measured, the present data are very limited in their ability to support inferences regarding the tendency for such headlamps to contribute to headlamp glare. Inspection of Figures IV-5 and IV-6, however, do indicate that a substantial percentage of the headlamps in the samples measured will produce some light above the horizontal plane; such light has the potential to create glare for oncoming and preceding drivers. Based on the results of a recent NHTSA study regarding the visibility of drivers with downwardly aimed headlamps (Akashi et al., 2008), such headlamps might reduce forward visibility.

Obviously, the vehicle sample evaluated in the present study was limited in size, but despite the limited sample, headlamp mis-aim was not a rarity. The present data do indicate that headlamps on stationary, level vehicles are often mis-aimed, in both the upward and downward directions. These findings have implications for forward visibility and for glare.

Requiring new vehicles to have properly aimed headlamps at the time of sale could be a countermeasure to decrease the likelihood of improper aim for new and recent model year vehicles. Since there was little relationship between vehicle age and headlamp aim status found in the present study, it cannot be stated whether periodic (e.g., annual) aim adjustment would improve headlamp aim significantly overall. While there were minor differences in headlamp aim compliance (~10%) between two states that differed in their headlamp safety inspection policies, it seems probable that everyday vehicle use contributes to the majority of mis-aimed headlamps within a relatively short period of time (e.g., less than one year). European vehicles used automatic headlamp leveling systems for some vehicle headlamp types; if the calibration of these systems can be maintained, and if the causes of headlamp mis-aim can be found with additional data to be solvable by such systems, then they might reduce the likelihood of headlamp mis-aim if they were to be implemented on vehicles in the U.S. fleet.

V. SURVEY OF DRIVER VISUAL NEEDS AND METRICS

Summary

Published literature on the vehicle lighting conditions required to provide for sufficient forward visibility of drivers at night while producing acceptable levels of glare was reviewed and is summarized in the present chapter. The findings imply that detection distance and reaction time metrics are both related to the visibility requirements of drivers and that they would yield similar conclusions in research studies. Subjective ratings of discomfort are at present the best and most reliable metric for characterizing discomfort glare. While the review yielded the tentative conclusion that most halogen low-beam headlamp patterns will provide acceptable levels of glare, it was also generally found that low-beam headlamps provide insufficient visibility to detect and respond to potential roadway hazards at many driving speeds above 30 to 40 mph (48 to 64 km/h). The review suggests that dynamic approaches to providing sufficient forward illumination while controlling glare through intensity reduction when other drivers are present could serve to provide adequate visibility without increasing glare to surrounding drivers.

Background

As described in a recent report from the National Highway Traffic Safety Administration (NHTSA, 2007) to the U.S. Congress on nighttime glare and driving performance, vehicle headlamps provide essential forward visibility to drivers at night, but inherently produce some level of glare to adjacent drivers because of their luminous intensity. The balance between visibility and glare is a trade-off that has been recognized throughout the history of automotive headlamps (Gaudaen, 1996). In general, headlamps with higher luminous intensities will increase visibility, but at the same time will increase glare to other drivers.

The development of requirements for vehicle headlamps has tried to manage this inherent conflict between visibility and glare through the specification of two beam patterns (i.e., low- and high-beam headlamps) and through the specification of minimum and maximum luminous intensity values for specific angular locations within each headlamp beam pattern (Moore, 1998). In theory, drivers should use their high-beam headlamps as often as possible and only revert to the low-beam headlamps when there is a potential to create glare for other drivers (excluding conditions such as fog or snow when high-beam headlamps can be problematic). In practice, high-beam usage in the United States is quite low (Sullivan et al., 2004) and there has been more development and evolution in the design of the low-beam pattern, in which glare control is an important criterion alongside forward visibility (Moore, 1998). Much of the research conducted in recent decades and discussed in the present report has focused on the requirements for luminous intensity in the low-beam headlamp pattern to optimize the balance between visibility and glare.

The primary objective of the present report is to summarize existing published information regarding metrics and drivers' needs for visibility and to prevent glare. Following a brief overview of metrics and of visual needs for each of these responses, the methods and results from several studies of headlamp performance are provided in short annotations of key literature.

Visibility: Metrics and Visual Needs

Metrics

In order to develop meaningful specifications for headlamp luminous intensity to provide a minimum level of forward visibility, an operational definition, or metric, of visibility is needed. Nearly every experiment to assess the impacts of lighting on visibility has used a different operational definition of visibility. Metrics of visibility that have been used in studies of headlamp performance can be grouped into one of five broad categories:

- Detection distances for targets
- Response times to targets
- Detection probabilities for targets
- Ability to properly maintain lane position
- Subjective impressions of visibility

Complicating comparisons among different studies using similar metrics (e.g., detection distance) is the variety of target sizes, shapes, reflectances and locations within the field of view that have been used. Further, not all of the study authors provided results in a manner that can be readily tabulated.

Visual Needs

Despite the aforementioned difficulties when comparing the results of disparate experiments directly, Figure V-1 shows a sample of data from several investigations of detection distance (Falge, 1934; Roper and Howard, 1938; Padmos and Alferdinck, 1988; Kosmatka, 1992; Sivak and Flannagan, 1994). Detection distance is the most commonly used metric for characterizing headlamp performance among the studies that were reviewed. The data were all converted to illuminance (a function of luminous intensity and distance) on the target for various distances used in each study required for reliable detection. Many of the studies used pedestrian targets dressed in dark clothing (Falge, 1934; Roper and Howard, 1938; Kosmatka, 1992); others simply provided the levels required for detection of general hazards and did not define the target characteristics associated with a recommendation of light level.

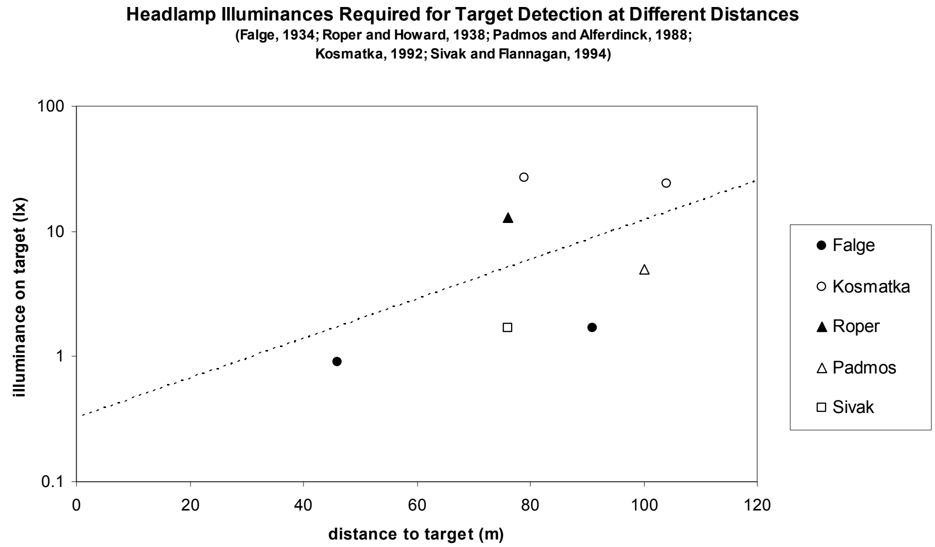


Figure V-1. *Illuminances on targets needed for visual detection at several distances, from several different studies.*

Inspection of Figure V-1 illustrates the difficulties in comparing different studies with one another. While there is an overall upward trend in terms of the illuminances required to see targets from further away (as expected based on the smaller apparent size of such targets), such illuminances for the same nominal distance can vary by as much as a log unit. Similar discrepancies among experimental results in various experiments have been described previously by Perel et al. (1983).

Aside from the quantitative, albeit imprecise, visual detection distance data in Figure V-1, the studies reviewed in the Annotations section of the report yield several qualitative conclusions regarding the visual needs of drivers as they are provided by vehicle headlamps:

- The visual needs as assessed by measuring detection distances appear to be consistent with those assessed by measurement of response times (Marmolin and Lisper, 1974; Akashi et al., 2003; Bullough, 2002).
- Lower luminous intensities (than typical low-beam headlamp patterns provide) can be used in locations with high ambient light levels, such as from roadway lighting (Fisher, 1974; Akashi et al., 2003, 2005).
- Typical low-beam headlamp patterns generally do not provide sufficient visibility to detect low-reflectance (<10%) targets in time to stop for driving speeds greater than 30 to 40 mph (48 to 64 km/h) (Roper and Howard, 1938; Johansson and Rumar, 1968; Padmos and Alferdinck, 1988; Kosmatka, 1992; Andre and Owens, 2001).
- Typical low-beam patterns conforming to U.S. luminous intensity requirements of Federal Motor Vehicle Safety Standard (FMVSS) 108 do not differ greatly in terms of visual performance from typical low beam patterns meeting European specifications (Mortimer and Olson, 1974; Irving and Yerrell, 1975; Olson, 1977; Perel, 1985).

Glare: Metrics and Visual Needs

Metrics

Although the visibility from headlamps is the primary purpose for using them in the first place, specifications for headlamps do include controls to limit glare. As described in NHTSA's (2007) report on nighttime glare and driving performance, glare has been defined in various studies of headlamp performance using several different metrics. These in turn can be categorized into three types: disability glare, defined as reductions in one's ability to see in the presence of bright lights; discomfort glare, defined as the annoying or painful sensations elicited by bright lights; and visual recovery, defined as the period of time following exposure to bright lights during which visibility is reduced.

Regarding disability glare, this has been defined in terms of several metrics similar to those used to characterize visibility:

Changes in detection distances for targets
Changes in response times
Changes in detection probabilities

Discomfort glare, unlike disability glare, has been more difficult than disability glare to measure reliably, in part because discomfort glare is influenced by psychological factors as well as physiological factors (Rea, 2000; Theeuwes et al., 2001; Bullough et al., 2002, 2003). As such, control and documentation of the visual conditions used in studies of discomfort glare is important, perhaps even more so than for studies of disability glare. While physiological metrics have been attempted in the measurement of discomfort glare, the best and most reliable metric for discomfort glare is a subjective rating technique. Most commonly in the field of vehicular lighting, the De Boer (1967) scale (1=unbearable, 9=just noticeable glare) has been used.

Visual recovery differs from disability glare because it is a phenomenon occurring *after* vehicle headlamps are no longer present in the field of view. Visual sensitivity to objects in the field of view is a function of the visual adaptation level, which in turn is increased by the presence of headlamps in a scene. Re-adaptation by a driver's eyes to a lower light level is a relatively slow biological response, and can take several seconds under visual conditions experienced while driving at night (Chen, 2004; Van Derlofske et al., 2005). During this re-adaptation period, visual sensitivity is reduced and objects are more difficult to see than they would otherwise have been before exposure to oncoming headlamps. Several studies have been conducted to assess visual recovery in the contexts of vehicle headlamps (Baker, 1963; Irikura et al., 1999; Lehnert, 2001) and of aviation (Boyer, 1976; Adams et al., 1979; Reddix et al., 1990; Kosnick and Smith, 2003; Beer, 2004). In general, these studies have used variations on the same basic task involving measuring the time to detect objects in the visual scene following the presentation of a bright light.

Visual Needs

As with the studies of visibility, most of the studies of visual requirements to help minimize the effects of glare following exposure to bright light have used disparate visual conditions (e.g., light levels, targets, experimental protocols) that make direct quantitative comparison of the results difficult. The studies reviewed in the Annotations section of the present report yielded the following qualitative conclusions regarding drivers' visual requirements pertaining to glare:

Disability Glare:

- Targets having higher reflectances and targets located closer to the line of sight are more "resistant" to glare in terms of detection probabilities (Bullough and Van Derlofske, 2004; Wood et al., 2005).
- The presence of oncoming headlamp illumination can reduce detection distances by 15 to 60 m (Dunipace et al., 1974; Perel et al., 1983).
- Detection distances to targets in the presence of oncoming headlamp illumination (when both a driver's headlamps and oncoming headlamps are the same type) are longer when both vehicles use high-beam headlamps than when they both use low beams (Helmers and Rumar, 1975).

Discomfort Glare:

- Differences between low-beam headlamps meeting U.S. and European specifications in terms of elicited discomfort glare are small, with European headlamp patterns generally producing slightly less discomfort (Mortimer and Olson, 1974; Perel, 1985; Sivak et al., 1998; Draper, 2007).
- Reducing headlamp intensity in urban areas will reduce discomfort glare to oncoming drivers (Fisher, 1974).
- Raising the mounting height of headlamps will tend to produce higher levels of discomfort glare (Akashi et al., 2005).

Visual Recovery:

- Visual recovery following glare appears to be related to the "dosage" of exposure experienced, in terms of illuminance × duration of exposure (Kosnik and Smith, 2003).
- Visual recovery times for high-reflectance targets are shorter than those for low-reflectance targets under the same oncoming illuminance exposure conditions (Adams et al., 1979).

Discussion

It is clear from the summaries of visual needs pertaining to visibility and glare in the preceding sections of this report that it is difficult to derive precise quantitative limits and specifications of headlamp photometric performance. However, despite the disparity in specific results, which are most likely caused by differences in visual targets, instructions to subjects, and ambient conditions (Perel et al., 1983), the studies reviewed in this report yield largely consistent qualitative trends regarding the impacts of headlamp intensity and headlamp beam distribution characteristics on visibility and glare.

Visibility

Regarding driver needs from lighting for visibility, it is likely that studies involving measures of response times (e.g., Marmolin and Lisper, 1974; Bullough, 2002; Bullough and Van Derlofske, 2004) will produce consistent results as those involving measurement of detection distances. Marmolin and Lisper (1974) suggest that response times might be a useful metric compared to visual detection metrics (i.e., detection distance) because it is relatively straightforward to implement without complicated study procedures, because response times are fairly sensitive to small changes in visual and lighting conditions, and because response times have inherent face validity in understanding how drivers might respond to potential hazards in the scene.

The studies further suggest that although there are not large differences among U.S. and European low-beam headlamp patterns (which, in general, consider driver visibility and glare control, respectively, as primary performance criteria) in terms of visibility, low beams in general do not provide sufficient stopping distances at realistic driving speeds (e.g., higher than 30 mph). The small differences in performance between U.S. and European low-beam patterns suggest that subsequent modifications to low beam specifications might not yield large differences in visibility. Rather, the results suggest that investigation of headlamp beam patterns with higher luminous intensities are one way to provide improved visibility, and perhaps the only way at higher driving speeds.

Glare

The studies evaluated in the present report, in general, confirm the inherent conflict between increasing headlamp intensity to improve forward visibility and limiting intensity to prevent glare for other drivers. Taking into account only the visual performance of drivers in the presence of glare, the published evidence suggests that increasing the intensity of all vehicle headlamps would improve visibility, even if all drivers used high-beam headlamps continuously (Helmers and Rumar, 1975). However, despite visibility improvements, drivers would probably not accept the increased discomfort that such lighting conditions would produce. At present, subjective ratings are the most reliable and useful metrics for characterizing discomfort glare.

Sivak et al. (1992) suggest that an illuminance of about 1 lx at the eyes of a driver from oncoming headlamps is a reasonable limit for the control of discomfort glare, eliciting subjective ratings on the De Boer (1967) scale that correspond to values between "just acceptable" and "disturbing." As with visibility, the studies do not suggest that low beam patterns meeting U.S. photometric requirements differ greatly from those meeting European specifications, although there is a slight trend of reduced discomfort glare with the latter headlamp beam patterns (Mortimer and Olson, 1974; Perel, 1985; Sivak et al., 1998). Most such headlamps produce 1 lx or less toward oncoming drivers. A caveat that should be recognized is that HID headlamps tend to have a "bluer" color appearance than halogen headlamps. Although headlamp color does not appear to impact disability glare, HID headlamps can be equivalent to halogen headlamps having intensities 25 to 50 percent higher in terms of discomfort glare (Bullough et al., 2002, 2003), because the mechanisms for discomfort glare appear to have increased sensitivity to the short-wavelength ("blue") portion of the visible spectrum.

Regarding glare recovery, the "dosage" (Kosnik and Smith, 2003) delivered to the eyes of an adjacent driver seems to be the most relevant photometric parameter to predict the speed with which one can re-adapt visually to the light levels on the roadway following exposure to headlamp illumination.

Conclusions

If the limitations of present-day low beam headlamp patterns regarding visibility, particularly for driving speeds greater than 30 mph (48 km/h) are to be overcome, luminous intensities that produce higher illuminances on potential hazards in and along the roadway are likely necessary. Such intensities will almost certainly produce unacceptable levels of glare for surrounding drivers, even if low beam headlamp patterns are modified as discussed by several researchers (Meese and Westlake, 1971; Huculak, 1978; Halstead-Nussloch et al., 1979; Olson and Sivak, 1983; Bhise et al., 1984; Perel, 1985; Padmos and Alferdinck, 1988; Helmers et al., 1990; Nakata et al., 1992; Rumar, 1998; Sato et al., 2001).

Optical control of luminous intensity distributions from headlamps has improved in recent decades (Rosenhahn and Lampen, 2004) and location-specific intensity reductions to mitigate glare can be implemented feasibly on vehicle lighting systems. A form of adaptive forward-lighting systems (AFS) that utilizes a headlamp beam pattern with increased (relative to low beam patterns) intensity, while able to reduce intensity in region(s) that would be directed toward oncoming drivers, could be an innovative solution to the inherent conflict between visibility and glare. Development and evaluation (using metrics identified in the present report) of such a system is one research activity undertaken by NHTSA in its forward-lighting research program, and is documented in a separate report describing AFS approaches for glare control.

Adams, A. J., Haegerstrom-Portnoy, G., and Brown, B. (1979). Night Vision Performance in Detection and Identification of Moving Targets After Glare, AD-A106719. Frederick, MD: U.S. Army Medical Research and Development Command.

Metrics:

- Contrast thresholds and recovery times for detecting and resolving moving and stationary targets were measured.

Visual Needs:

- Detection sensitivity was highest for moving targets, and resolution sensitivity was highest for stationary targets.
- Glare recovery time (after 10-s exposure to 12,000 cd/m² luminance) was linearly related to the contrast of both moving and stationary targets for detection and resolution, but were always longer for stationary targets.

Akashi, Y., Dee, P., Chen, J., Van Derlofske, J., and Bullough, J. (2003). Interaction between fixed roadway lighting and vehicle forward lighting. Progress in Automobile Lighting Symposium 2003 (pp. 11-22), Darmstadt University of Technology, Germany, September 23-24. München, Germany: Herbert Utz Verlag.

Metrics:

- Target detection distance was measured under different headlamp and roadway lighting intensities.

Visual Needs:

- Reduction of headlamp intensity to 10 percent of its original value resulted in small but measurable reductions in target detection distance in areas with fixed roadway lighting.
- Reductions in fixed roadway lighting illuminance to 10 percent of its original value resulted in larger reductions in target detection distance.
- For targets located 15^{o} to the right of the line of sight, the effect of headlamp illumination was greater than that of roadway lighting illuminance.

Akashi, Y., Van Derlofske, J., and Bullough, J. D. (2005). Recommendations for dimming headlamps through AFS. International Symposium on Automotive Lighting (pp. 890-899), Darmstadt University of Technology, Germany. München, Germany: Herbert Utz Verlag.

Metrics:

- Discomfort glare ratings to following and oncoming headlamps varying in height were measured.

Visual Needs:

- Reductions in headlamp intensity resulted in reductions in discomfort glare in both following- and oncoming-vehicle scenarios.
- Increases in headlamp mounting height, especially close to the maximum allowable height, increased discomfort glare.

Andre, J., and Owens, D. A. (2001). The twilight envelope: A user-centered approach to describing roadway illumination at night. *Human Factors, 43*(4), 620-630.

Metrics:

- An illuminance corresponding to the lower end of civil twilight (3.3 lx) is proposed as a measure of the level at which visibility is reduced unacceptably.

Visual Needs:

- Civil twilight distances of 175 ft (at headlamp height), 260 ft (at ground level) and 80 ft (at eye height) are reported for low beam illumination.
- Stopping distances at most speeds are longer than the civil twilight distances, indicating potential risk.

Beer, J. (2004). Disruption of Visual Flight Control in a Synthetic Cockpit Resulting from Continuous Versus Discontinuous Laser Glare. Brooks City Base, TX: Naval Health Research Center.

Metrics:

- Subjects performed a flight approach landing task under different laser glare conditions (continuous and various strobing conditions).

Visual Needs:

- Performance was usually better under the strobing conditions except for the highest flash rates and duty cycles, indicating that visual recovery was possible between flashes.

Bhise, V. D., Matle, C. C., and Hoffmeister, D. H. 1984. Chess model applications in headlamp systems evaluation (SAE paper 840046). Warrendale, PA: Society of Automotive Engineers.

Metrics:

- Using a computer model of headlamp performance (Chess), the effects of mis-aim, mounting height, and beam patterns on visibility and discomfort were investigated.

Visual Needs:

- Mis-aim (selected randomly from previously published mis-aim statistics) reduced the predicted percentage of visible roadway delineations and pedestrian targets, and increased the predicted percentage of oncoming drivers experiencing discomfort.
- Lower mounting heights decreased visibility and decreased discomfort to oncoming drivers.
- A "high-output" beam with a maximum luminous intensity twice that of a conventional low beam but restricting most light to the right of center and below horizontal appeared to increase visibility but also increased discomfort glare to oncoming drivers.

Boyer, D. A. (1976). Glare Recovery of a Two Dimensional Tracking Task With Respect to Various Colors, ITC-02-08-76-015. Texarkana, TX: Texas A&M University Graduate Center.

Metrics:

- Subjects performed a tracking task of different colors following exposure to a glare source consisting of automotive headlamps.

Visual Needs:

- Performance of the task was best when the tracking task was illuminated by blue light, relative to white, red, or orange-red light.

Bullough, J. D. (2002). Modeling peripheral visibility under headlamp illumination. Transportation Research Board 16th Biennial Symposium on Visibility and Simulation. Iowa City, IA, June 2-4, 2002.

Metrics:

- A model of driver visual performance based on response times and detection probability to small targets was developed.

Visual Needs:

- For targets (20%-40% reflectance, 20 cm square), vertical illuminances of about 2 lx are required to ensure rapid and accurate detection for targets 2.5^{o} off-axis.
- For the same targets, vertical illuminances of about 5 lx are required to ensure rapid and accurate detection for targets 12.5^{o} off-axis.
- For the same targets, vertical illuminances of about 10 lx are required to ensure rapid and accurate detection for targets 17.5^{o} off-axis.

Bullough, J. D., and Van Derlofske, J. (2004). Headlamp illumination and glare: An approach to predicting peripheral visibility. Society of Automotive Engineers 2004 World Congress, Detroit, MI, March 8-11. In Lighting, SP-1875 (pp. 181-186). Warrendale, PA: Society of Automotive Engineers.

Metrics:

- The model of peripheral visibility proposed by Bullough (2002) is extended to incorporate the influence of oncoming headlamp glare on response times and target detection probabilities.

Visual Needs:

- Targets with higher reflectances are less sensitive (in terms of visual detection) to glare than those with lower reflectances.

Draper, G. R. (2007). Performance assessment of vehicle headlamps. 18th Biennial Transportation Research Board Visibility Symposium, April 17-18, College Station, TX.

Metrics:

- Discomfort glare and pedestrian detection are considered under various headlamp systems.

Visual Needs:

- Reference to previous experiments is made suggesting that from 50 m away, all headlamps among those investigated produced acceptable levels of glare.
- It is stated that discomfort glare is less problematic and severe than disability glare.
- A vertical illuminance of 3 lx on a 5 percent reflectance target is used as a minimum criterion for pedestrian visibility.
- The location of highest probability of an oncoming driver's eyes 50 m ahead is 1.1 to 1.2 m above the ground, and about 2.3 m to the left of one's own vehicle.

Dunipace, D. W., Strong, J., Huizinga, M. (1974). Prediction of nighttime driving visibility from laboratory data. *Applied Optics 13*(11), 2723-2734.

Metrics:

- Target detection distances were calculated from a model developed from visual threshold data.

Visual Needs:

- With low beams, detection distances with glare present were 15 m to 60 m shorter than without glare.
- Without glare present, detection distances with high beams were 15 m to 60 m longer than with low beams.

Falge, R. N. (1934). Modern headlighting requirements (SAE paper 340095). Warrendale, PA: Society of Automotive Engineers.

Metrics:

- Headlamps were evaluated by determining the necessary luminous intensity to see pedestrians in clothing of varying lightness at different viewing distances.

Visual Needs:

- Pedestrians in black clothing required 1900 cd to be seen at 150 ft, and 14,000 cd to be seen at 300 ft.
- Pedestrians in gray clothing required 450 cd to be seen at 150 ft, 3300 cd to be seen at 300 ft, and 14,000 cd to be seen at 500 ft.
- Pedestrians in light clothing required 240 cd to be seen at 150 ft, 1800 cd to be seen at 300 ft, 7700 cd to be seen at 500 ft and 20,000 cd to be seen at 700 ft.

Fisher, A. J. (1974). The luminous intensity requirements of vehicle front lights for use in towns. *Ergonomics 17*(1), 87-103.

Metrics:

- Using subjective appraisals, the required intensity of vehicle forward lighting was determined for urban areas to ensure conspicuity while avoiding discomfort glare.

Visual Needs:

- A luminous intensity of 80 cd was determined to be optimal for conspicuity and discomfort glare.

Gallagher, V. P., Janoff, M. S. (1972). Interaction Between Fixed and Vehicular Illumination Systems, FHWA-RD-72-51. Washington, DC: Federal Highway Administration.

Metrics:

- The authors assessed visibility under various vehicle lighting conditions (high/low beams, parking lamps) and roadway light levels and uniformity levels, using detection distance and left-turn gap acceptance as dependent measures.

Visual Needs:

- In locations with roadway illumination, parking lamps were insufficient to provide good judgment of gaps in traffic for turning left.
- In locations with roadway illumination, high beams did not result in greater visibility distances than low beams.

Gallagher, V. P., and Meguire, P. G. (1974). Contrast Requirements of Urban Drivers, FHWA-RD-74-76. Washington, DC: Federal Highway Administration.

Metrics:

- A series of field experiments of driving performance along various urban roadways was conducted using time and distance to a hazard as the measure of performance.

Visual Needs:

- Luminance contrast of the relevant visual elements in the roadway were well correlated with the performance measures.

Hagiwara, T., Morishita, M, Horii, Y., Miki, K., and Ohshima, I. (2007). Preferences for headlight swivel angles at curves on rural two-lane highways. *Transportation Research Record, 2030,* 47-53.

Metrics:

- Headlamp configurations involving swiveling headlamps were evaluated in terms of driver preference at three locations: two in advance of a curve and one at the entrance to the curve.

Visual Needs:

- When approaching a left curve (in Japan; equivalent to a right curve in the U.S.), drivers preferred swivel angles of less than 5^o.
- When entering a left curve, drivers preferred swivel angles close to 5^o.
- For right curves (in Japan; equivalent to a left curve in the United States), drivers preferred swivel angles greater than 15^o when approaching the curve.
- When entering a right curve, drivers preferred swivel angles of about 15^o.

Halstead-Nussloch, R., Olson, P. L., Burgess, W. T., Flannagan, M. J., and Sivak, M. (1979). Evaluation of the Feasibility of a Single-Beam Headlighting System, UM-HSRI-79-91. Ann Arbor, MI: University of Michigan.

Metrics:

- Headlamp systems were evaluated using target detection distances and subjective ratings of visibility.

Visual Needs:

- Based on an analysis of likely locations of oncoming drivers' eyes, signs and other potential roadway hazards, headlamp systems producing more illumination to the right and up, to the left and down, and combining both approaches were investigated in simulation and field studies.
- Improvements from additional illumination were slight, but could be found.

Harris, A. J. [n.d.] Design of the Meeting Beam of the Automobile Headlight, No. 40. London, UK: Road Research Laboratory.

Metrics:

- Visibility distances were evaluated analytically using different headlamp beam patterns and different vertical aim angles in vehicle meeting scenarios.

Visual Needs:

- No visibility improvements above the standard low beam pattern were found among the beam patterns studied.
- With sharp cutoff headlamp beam patterns, deviations from vertical aim were not expected to create significant reductions in visibility distances to oncoming drivers.

Helmers, G., Fernlund, M., and Ytterborn, U. (1990). Optimisation of the Low Beam Pattern of Illumination, 353A. Linkoping, Sweden: Swedish Road and Traffic Research Institute.

Metrics:

- Detection distances to targets located along the road were measured in oncoming vehicle situations, using European style low-beam headlamp patterns (with sharp cutoff distributions), with both forward and oncoming headlamps being identical.

Visual Needs:

- Increasing the luminous intensity just above and just below the cutoff location reduced visibility distances.
- Increasing the ratio of intensities in the area just below to the intensities in the area just above the cutoff resulted in the longest visibility distances.

Helmers, G., and Rumar, K. 1975. High beam intensity and obstacle visibility. *Lighting Research and Technology, 7*(1), 35-42.

Metrics:

- Visibility distances for 1 × 4 m gray targets were measured experimentally under different combinations of forward headlamps and oncoming headlamps.

Visual Needs:

- As the maximum luminous intensity was increased (and as the intensity of an oncoming set of headlamps increased correspondingly), the visibility distances increased.

Hemion, R. H. (1968). The Effect of Headlight Glare on Vehicle Control and Detection of Highway Vision Targets, AR-640. San Antonio, TX: Southwest Research Institute.

Metrics:

- The effectiveness of different headlamp beam patterns was evaluated by measuring detection distances to pedestrian targets located along the roadway.

Visual Needs:

- Detection distances were greater when both the subjects' vehicle and the oncoming vehicle used high-beam headlamps than when they both used low beams.
- Detection distances were unaffected by driving speed between 30 and 55 mph.
- Dirty windshields decreased detection distances.

Huculak, P. (1978). A Visibility Analysis of Obstacle Detection Experimentation in Unopposed Automotive Headlighting, NRC No. 16780. Ottawa, ON: National Research Council Canada.

Metrics:

- Detection probabilities to targets in the center of the driving lane were measured under different target and headlighting conditions and at different distances in order to estimate visibility distances.

Visual Needs:

- The luminance difference between a target and its background was found to be the primary predictive parameter related to visibility distance.
- Increased foreground illumination in most cases had small negative impacts on visibility distances.

Huculak, P. (1978). The Influence of Glare on the Detection of Hazardous Objects in Automobile Night Driving, NRC No. 16891. Ottawa, ON: National Research Council Canada.

Metrics:

- Detection probabilities to targets in the center of the driving lane were measured under different target and headlighting conditions (including oncoming glare) and at different distances in order to estimate visibility distances.

Visual Needs:

- Detection distances were longer when opposed by a headlamp that had higher intensities than a typical low beam at higher than normal angles (but still below horizontal), and that had a sharp cutoff producing lower than normal light levels at oncoming drivers' eyes.

Irving, A., and Yerrell, J. S. (1975). Lighting research at the U.K. Transport and Road Research Laboratory. In: Driver Visual Needs in Night Driving, Special Report 156. Washington, DC: Transportation Research Board.

Metrics:

- Target detection distances to roadway objects are reported.

Visual Needs:

- No significant advantages are reported (in terms of visibility distances) between U.S./U.K. types of headlamp low beam patterns and European beam patterns with sharper cutoffs.

Johansson, G., and Rumar, K. (1968). Visible distances and safe approach speeds for night driving. *Ergonomics, 11*(3), 275-282.

Metrics:

- Pedestrian detection distances with low-beam headlamps in oncoming vehicle scenarios were investigated experimentally.

Visual Needs:

- Detection distances from low beams when meeting oncoming low beams averaged 23 m.
- The estimated safe driving speeds corresponding to such detection distances ranged from 25 to 50 km/h (16 to 31 mph).

Kosmatka, W. (1992). Obstacle detection rationale for upper beam intensity. Minutes of the Society of Automotive Engineers Headlamp Beam Pattern Task Force, Nashville, TN.

Metrics:

- A model to predict detection distances based on the luminances of targets is presented.

Visual Needs:

- At a driving speed of 55 mph, a luminous intensity of 166,000 to 180,000 cd is required to detect low-reflectance objects in time to stop.
- At a driving speed of 65 mph, a luminous intensity of 243,000 to 264,000 cd is required to detect low-reflectance objects in time to stop.

Kosnik, W., and Smith, P. (2003). Flashblindness and Glare Modeling of Optical Radiation, AFRL-HE-BR-TR-2003-0069. Brooks City-Base, TX: U.S. Air Force Research Laboratory.

Metrics:

- Authors evaluated (analytically) contrast thresholds and recovery times associated with glare sources.

Visual Responses:

- A model of disability glare when small targets are nearly coincident with a glare source is provided.
- A model of recovery from flashblindness is derived that is based on the light-energy (retinal illuminance × duration) from the glare source.

Marmolin, H., and Lisper, H. O. (1974). Reaction Time as a Measure of Night Vision Ability, Report 158. Uppsala, Sweden: University of Uppsala.

Metrics:

- Measurement of reaction times is proposed as being more efficient than threshold visibility measures.

Visual Needs:

- Reaction time measurement is proposed as a useful indicator of nighttime visibility.
- Studies using reaction time measures are stated to provide consistent information as those using threshold detection measures.

McLean, J. R., and Hoffmann, E. R. (1973). The effects of restricted preview on driver steering control and performance. *Human Factors, 15*(4), 421-430.

Metrics:

- Drivers' ability to maintain a vehicle within a driving lane was measured under different conditions of foreground illumination.

Visual Needs:

- As long as drivers had 21 m of preview distance (illuminated roadway surface ahead of the vehicle) they were able to keep the vehicle within the lane edges.

Meese, G. E., and Westlake, P. W. (1971). Key factors in evaluating headlighting systems. Proceedings of the 17th Session of the Commission Internationale de l'Éclairage, Barcelona, Spain.

Metrics:

- The authors measured visibility distances with different headlamps and different mounting heights.

Visual Needs:

- In general, greater visibility distances were found using headlamps with higher luminous intensities 0.5° down and 2° to the right of center.
- Detection distances to targets 1.75 m high were about 20 percent longer than to targets 0.4 m high.
- Detection distances were about 17 m longer with headlamp mounting height moved from 66 to 79 cm above the ground.

Mortimer, R. G., Becker, J. M. (1973). Development of a Computer Simulation to Predict the Visibility Distance Provided by Headlamp Beams, UM-HSRI-HF-73-15. Ann Arbor, MI: University of Michigan.

Metrics:

- Using a series of calculations based on visual theory and confirmed by experimental studies, the authors estimated visibility distances to targets under different lighting conditions including oncoming headlamps.

Visual Needs:

- Forward headlamps of increased intensities result in longer visibility distances.
- As the intensity of oncoming headlamps increases, visibility distances decrease.

Mortimer, R. G., and Olson, P. L. (1974). Development and Use of Driving Tests to Evaluate Headlamp Beams, UM-HSRI-HF-74-14. Ann Arbor, MI: University of Michigan.

Metrics:

- Visibility distances to targets were measured during dynamic driving studies.

Visual Needs:

- Low beams meeting then-common standards for U.S. headlamps outperformed European headlamp low beams in terms of visibility distances.
- The European low beam pattern produced less discomfort glare to oncoming drivers than the U.S. low beam pattern (although both beam patterns produced relatively low amounts of glare).

Nakata, Y., Ushida, T., and Takeda, T. (1992). Computerized graphics light distribution fuzzy evaluation system for automobile headlighting using vehicle simulation (SAE paper 920816). Warrendale, PA: Society of Automotive Engineers.

Metrics:

- Headlamp beam distributions were evaluated analytically with respect to detection distance and discomfort glare.

Visual Needs:

- A proposed "good" low-beam headlamp distribution has increased intensity 0.5º down and toward the passenger's side of the vehicle for improved target detection.
- The cutoff from the driver's side to the passenger side should form a "V" shape rather than a curved shape for improved glare control.

Olson, P. L. (1977). The Relative Merits of Different Low Beam Headlighting Systems: A Review of the Literature, UM-HSRI-77-55. Ann Arbor, MI: University of Michigan.

Metrics:

- The author reviews published research comparing then-current sealed beam headlamps with European beam patterns, primarily using visibility distances as the dependent variable.

Visual Needs:

- It is concluded that neither beam pattern type was inherently superior to the other.

Olson, P. L., and Sivak, M. (1983). Improved Low-Beam Photometrics, UMTRI-83-9. Ann Arbor, MI: University of Michigan.

Metrics:

- Using the then-current standards for low-beam headlamp photometric performance, the authors suggested modifications for improving detection distances.

Visual Needs:

- Generally, the proposed modifications increased the luminous intensity above horizontal and at the location of maximum luminous intensity.

Padmos, P., and Alferdinck, J. W. A. M. (1988). Optimal Light Intensity Distribution of the Low Beam of Car Headlamps, IZF 1988 C-9/E. Soesterberg, Netherlands: TNO Institute for Perception.

Metrics:

- The authors reviewed literature on visual detection of lane markings and potential roadway hazards with the objective of identifying the minimum intensity needed for reliable detection.

Visual Needs:

- Increased luminous intensity in the "hot spot" of the beam to about 50,000 cd is proposed as a means of increasing target detection at distances of 50 to 150 m.

Perel, M. (1985). Evaluation of headlamp beam patterns using the Ford CHESS program (SAE paper 856035). Warrendale, PA: Society of Automotive Engineers.

Metrics:

- Headlamp beam patterns were evaluated using the Comprehensive Headlamp Environment Systems Simulation (CHESS) program in terms of the number of oncoming drivers experiencing a De Boer discomfort rating of 4 and the number of pedestrian targets that would be detected.

Visual Needs:

- A U.S.-style low beam slightly outperformed a European-style low beam pattern in terms of pedestrian detection but resulted in slightly more glare.
- A modified beam pattern with higher intensity in the lower right (passenger side) quadrant resulted in a higher percentage of pedestrian targets detected.
- Vertical aim was one of the most important headlamp parameters (other than headlamp intensity) affecting pedestrian detection and oncoming driver discomfort.

Perel, M., Olson, P. L., Sivak, M., and Medlin, J. W. (1983). Motor vehicle forward lighting (SAE paper 830567). Society of Automotive Engineers International Congress and Exhibition, February 28-March 4, Detroit, MI.

Metrics:

- Studies of visibility distances to small (about 0.5 m square) or large (person-sized) low-reflectance (about 7%-10%) targets under low-beam headlamps, with and without glare are summarized.

Visual Needs:

- For small targets, visibility distances ranged from 45 to 125 m without glare, and 38 to 114 m with glare; average reduction with glare was 23 m.
- For large targets, visibility distances ranged from 51 to 122 m without glare, and 55 to 107 m with glare; average reduction with glare was 24 m.

Reddix, M. D., DiVietti, T. L., Knepton, J. C., and D'Andrea, J. A. (1990). The Effect of Three Levels of Laser Glare on the Speed and Accuracy of Target Location Performance when Viewing a Briefly Presented Visual Array, NAMRL-1359. Pensacola, FL: Naval Aerospace Medical Research Laboratory.

Metrics:

- Monochromatic green light (514 nm) at levels of 0.4, 1 and 2 lx were presented to subjects who were asked to identify a small rectangle in a display containing 119 larger rectangles, located randomly throughout the display, after fixating on a crosshair target in the center of the display.

Visual Needs:

- Response times exhibited a dose-response relationship that appeared to begin to saturate between 1 and 2 lx; effects were largest for targets closest to the line of sight.

Roper, V. J., and Howard, E. A. (1938). Seeing with motor car headlamps. *Transactions of the Illuminating Engineering Society, 33*(5), 417-438.

Metrics:

- Detection distances to low-reflectance pedestrian targets are reported under various lighting and glare conditions.

Visual Needs:

- A minimum intensity of 75,000 cd is required to detect a target with sufficient time and distance to stop a moving vehicle initially traveling 50 mph.
- An oncoming headlamp intensity of 1000 cd reduces visibility distances by one-third; an intensity of 7000 cd reduces visibility distances by two-thirds.

Rumar, K. (2000). Relative Merits of the U.S. and ECE High-Beam Maximum Intensities and of Two and Four Headlamp Systems, UMTRI-2000-41. Ann Arbor, MI: University of Michigan.

Metrics:

- Through a literature review of previous studies, the author compared U.S. and European high-beam headlamp patterns (having maximum intensities of 75,000 and 140,000 cd, respectively) in terms of visibility distance, dimming distance and usage patterns of high beams.

Visual Needs:

- Visibility distances increase monotonically as a function of increased headlamp intensity, with relatively small increases after 150,000 cd (U.S. low beams had maximum intensities of 75,000 cd at the time of the review).
- The increase in dimming distance between headlamps with intensities of 60,000 cd and of 105,000 cd was about 15 percent.
- It is stated based on experience that high beams are used more frequently in Europe than in the United States, suggesting that they might be more effective.

Rumar, K. (1998). Vehicle Lighting and the Aging Population, UMTRI-98-9. Ann Arbor, MI: University of Michigan.

Metrics:

- Literature on visual performance of older drivers is reviewed and recommendations for improving headlamp beam patterns are made; the primary visual responses considered are detection distances and discomfort glare.

Visual Needs:

- It is recommended that headlamps increase intensity in the direction ahead (even though this will increase glare), to reduce the sharpness of the cutoff, to increase beam width for curves, and to decrease foreground illumination.

Sato, T., Kojima, S., and Matsuzaki, M. (2001). The smart headlamp system with variable low-beam pattern (SAE paper 2001-01-0854). Warrendale, PA: Society of Automotive Engineers.

Metrics:

- Headlamp beam patterns providing additional illumination ahead or to the sides were evaluated for visibility by calculating the distance at which the illuminance on the roadway is 5 lx.
- The same beam patterns were evaluated for discomfort glare by calculating the De Boer rating using the model of Schmidt-Clausen and Bindels (1974).

Visual Needs:

- The additional illumination increased the distance at which 5 lx was produced by 8 to 23 m.
- The discomfort glare in each situation was also increased by ~0.1 to ~0.7 De Boer units.

Schmidt-Clausen, H. J. (1982). The visibility distance of a car-driver in driving situation (SAE paper 820416). Warrendale, PA: Society of Automotive Engineers.

Metrics:

- Visibility distances to pedestrian targets were evaluated analytically under different headlamp conditions including oncoming glare.

Visual Needs:

- Visibility distances decreased as oncoming vehicle distances decreased between 150 m and 50 m.
- Dirt on headlamps decreased visibility distances.

Schmidt-Clausen, H. J., Damasky, J. (1994). The Field of Vision of Drivers During Nighttime, 94 S2 O 05. Darmstadt, Germany: Technical University of Darmstadt.

Metrics:

- Angular locations (relative to drivers' eyes) of overhead and shoulder-mounted traffic signs and of roadway markings were calculated from processed video footage.

Visual Needs:

- Angular regions of 3^o-4^o up for overhead signs, 1^o-2^o up/2^o-3^o right for shoulder-mounted signs, and 1^o down/5^o left-5^o right for roadway markings were found.

Sivak, M., and Flannagan, M. J. (1994). Recent steps toward international harmonization of the low-beam headlamp pattern. *International Journal of Vehicle Design, 15*(3/4/5), 223-233.

Metrics:

- Luminous intensity values at two points above horizontal are used as a stand-in for glare, and at two points below horizontal for forward visibility.

Visual Needs:

- Minimum luminous intensities of 10,000 cd at 0.5^o down and 1.25^o right, and of 1350 cd at 0.5^o down, 3.5^o left are recommended for visibility.
- Maximum luminous intensities of 750 cd at 0.5^o up and 1.5^o left, and of the actual value at 0.5^o down and 1.25^o right are recommended for glare control.

Sivak, M., Flannagan, M. J., and Miyokawa, T. (1998). Quantitative Comparisons of Factors Influencing the Performance of Low-Beam Headlamps, UMTRI-98-42. Ann Arbor, MI: University of Michigan.

Metrics:

- Using the luminous intensity values of a market-weighted headlamp beam pattern at several angular locations pertaining to visibility and glare, the authors compared the change in luminous intensity created by mis-aim, differences in mounting height, burned out headlamps, and other factors.

Visual Needs:

- The vertical mis-aim was almost always the most important factor affecting luminous intensity relevant to both visibility and glare.
- Burned out headlamps were often the second-most important factor.
- Differences in beam patterns (U.S.- versus European-style) and mounting height (passenger car versus light truck/sport utility vehicle) had modest effects on luminous intensities.

Sivak, M., Flannagan, M. J., Traube, E. C., Aoki, M., and Sayer, J. R. (1994). Evaluation of an Active Headlighting System, UMTRI-94-17. Ann Arbor, MI: University of Michigan.

Metrics:

- An active low-beam headlamp system that turned one headlamp right or left 15^o upon entering a curve was evaluated by measuring detection distance to a darkly clothed pedestrian.

Visual Needs:

- Detection distances improved over the standard condition (no headlamp turning) 2 percent and 15 percent for right and left turns, respectively.

Sivak, M., Helmers, G., Owens, D. A., Flannagan, M. (1992). Evaluation of Proposed Low-Beam Headlighting Patterns, UMTRI-92-14. Ann Arbor, MI: University of Michigan.

Metrics:

- Several beam patterns are evaluated based on analyses considering target detection and discomfort glare.

Visual Needs:

- Visibility criteria include seeing near- and intermediate-distance targets (minimum of 33 lx recommended), roadway delineations on hills and sags (minimum of 6.4 lx recommended), and traffic signs (minimum of 0.02 lx recommended).
- Glare control criteria include direct oncoming glare (maximum of 0.7 lx recommended) and rear view mirror glare (maximum of 11 lx recommended).

Sivak, M., Schoettle, B., Flannagan, M. J., and Minoda, T. (2005). Optimal strategies for adaptive curve lighting. *Journal of Safety Research, 26*, 271-288.

Metrics:

- Different headlamp configurations were assessed using the 3-lx illuminance criterion as a metric for forward visibility distance.

Visual Needs:

- Headlamp swiveling strategies involving swiveling both lamps in parallel, one lamp only, or different amounts for each headlamp were compared using a 3-lx illuminance criterion for curves of different radii.
- Swiveling both lamps in parallel provided the greatest 3-lx distances for small-radius curves and were more or less equally effective as other strategies for large-radius curves.

Smiley, A. (1974). Steering Wheel Response Under Various Headlighting Conditions, LTR-ST.108. Ottawa, ON: National Research Council Canada.

Metrics:

- The author measure high-frequency steering corrections as a measure of stress or visual difficulty under various lighting conditions.

Visual Needs:

- The greatest amount of high-frequency steering corrections were found when drivers used low beams but were met by vehicles displaying high beams.
- Unopposed drivers using both low and high beams had the lowest amount of high-frequency steering correction.

Sullivan, J. M., and Flannagan, M. J. (2002). Some characteristics of pedestrian risk in darkness. Transportation Research Board 16th Biennial Symposium on Visibility and Simulation. Iowa City, IA, June 2-4, 2002.

Metrics:

- Crash rates for the period of clock time that switches from light to dark (and vice versa) at the transition to and from daylight savings time were investigated to determine the role of ambient light on crash safety.

Visual Needs:

- Pedestrian crashes, but not vehicle-to-vehicle crashes, were highly related to ambient light level (with greater crash frequencies during darkness).

Wood, J. M., Tyrrell, R. A., and Carberry, T. P. (2005). Limitations in drivers' ability to recognize pedestrians at night. *Human Factors, 47*(3), 644-653.

Metrics:

- Detection distances to pedestrians were measured under different lighting and clothing conditions.

Visual Needs:

- Overall, with no glare present and using low beams, drivers along a closed circuit detected 85 percent of pedestrians wearing white clothing but only 40 percent of those wearing black clothing.
- With no glare present and using high beams, drivers detected 95 percent of pedestrians wearing white clothing and 55 percent of those wearing black clothing.
- With glare present and using low beams, drivers detected 75 percent of pedestrians wearing white clothing and 5 percent of those wearing black clothing.
- With no glare present and using low beams, drivers detected 80 percent of pedestrians wearing white clothing and 35 percent of those wearing black clothing.
- Mean detection distances using low beams were 40 m for pedestrians wearing white and 6 m for those wearing black.
- Mean detection distances using high beams were 105 m for pedestrians wearing white and 20 m for those wearing black.

VI. GLARE RECOVERY FIELD STUDY

Summary

Oncoming headlamps while driving at night can produce instantaneous reductions in visibility and comfort, commonly termed disability glare and discomfort glare, respectively. The presence of oncoming headlamps in the field of view temporarily increases the visual adaptation level, reducing sensitivity to light and resulting in reduced visual capability for a short time following headlamp exposure while the visual system re-adapts to a lower light level. This report summarizes a field experiment performed to measure the effects of oncoming illuminance profiles with different photometric and temporal characteristics on visual recovery and subjective discomfort. Previous laboratory studies suggested that the time to detect visual targets in the field of view following headlamp illumination exposure is related to the dosage (defined as the integration of the illuminance-versus-time function) of light received at the eye, but that subjective ratings of discomfort are related to the peak illuminance received during a given exposure. Those studies used simple, constant-illuminance profiles, whereas illuminances from oncoming vehicle headlamps change over time. In the present study, an adjustable-output projector light source was used to produce four different, accurately simulated exposure profiles with different dosage and peak illuminances. Eleven subjects in two age groups (mean <50 and >50 years) were instructed to respond to the onset of targets located 5^o or 10^o off-axis presented after exposure to each of the headlamp exposure profiles, and to report their levels of discomfort from the exposure profile. Consistent with the previous laboratory study results, the time to detect the targets was correlated with the dosage, but rated discomfort was correlated with the peak illuminance from each profile. Older subjects had longer recovery times, but there were no differences between the age groups in terms of rated discomfort in this study. The results suggest that discomfort glare is not predictive of visual disability and that control of luminous intensity at isolated points within the distribution of headlamps is not sufficient to minimize glare recovery.

Introduction

Glare from oncoming headlamps is perceived as an important problem by the U.S. driving public (NHTSA, 2007). Oncoming headlamp illumination can have several effects:

- Reductions in visibility caused by scattered light from headlamps within the eyes of drivers (disability glare)
- Sensations of annoyance or pain while headlamps are in the field of view (discomfort glare)
- Deficits in visibility *following* exposure to illumination from headlamps that changes the adaptation level of the eyes (glare recovery)

The first two phenomena have been extensively studied in the context of nighttime driving (e.g., Flannagan, 1999; Bullough et al., 2002, 2003). Disability glare is a fairly well-understood phenomenon (Fry, 1954) that can be by a *veiling luminance* (e.g., a contrast-reducing luminous overlay) that can be predicted by the illuminance from the offending light source and its location in the field of view. Discomfort glare is less well-understood, especially in terms of the mechanisms underlying discomfort. Two conditions that produce equivalent amounts of disability glare can produce different amounts of discomfort. De Boer (1967) studied discomfort glare extensively in the context of roadway lighting and developed a rating scale for discomfort that is still used today in many studies of automotive vehicle lighting and glare. The ratings use a nine-point scale structured as a figure of merit (higher values mean "better" conditions). A value of 1 corresponds to unbearable discomfort, 3 to disturbing glare, 5 to just acceptable glare, 7 to a satisfactory level of glare, and 9 to a level where glare is just noticeable.

Following exposure to headlamp illumination, the visual system's sensitivity is reduced temporarily while the photoreceptors re-adapt to the prevailing light level. This misadaptation is caused by the relatively high brightness of headlamps, which increases the visual adaptation level (effectively, reducing the sensitivity of the visual system). Adaptation from low to high light levels is accomplished in a short amount of time, but adaptation from high to low levels takes longer, on the order of several seconds under typical nighttime driving conditions (Chen, 2004). During this recovery time, objects that are close to the visual threshold can be invisible immediately following exposure to a bright light until the adaptation level is reduced (and visual sensitivity is increased) enough to make them visible (Baker, 1963; Irikura et al., 1999; Lehnert, 2001). Logically, this temporary reduction in visual functioning has implications for nighttime driving safety.

Irikura et al. (1999) investigated the role of light source luminance and duration on visual recovery by measuring the time taken to recover visual acuity corresponding to half of that before exposure to the light source. Recovery times were strongly correlated with the "dosage" (defined by Irikura et al. as the product of luminance and duration) produced by the light source. In comparison, Sivak et al. (1999) measured discomfort glare of individuals exposed to sources varying in illuminance produced at the eye and in duration. While sources with the same illuminance but different dosages (defined by Sivak et al. as the product of illuminance and duration) resulted in slightly different subjective ratings of discomfort, the major factor influencing discomfort was the illuminance at the eye. Together, these results lead to a hypothesis that glare recovery and discomfort glare are mediated by different mechanisms. To further explore this hypothesis, Van Derlofske et al. (2005) measured both visual recovery and discomfort ratings to sources producing different illuminances and different dosages (defined as by Sivak et al. as the product of illuminance and duration). The results of that study were consistent with the hypothesis.

The age of a driver plays a role in the amount of time required for glare recovery. Older drivers have been reported to have longer recovery times than younger ones (Schieber, 1994). However, evidence for differences in discomfort glare between age groups is scarce and conflicting. Dee (2003) measured discomfort from lights varying in intensity and spectral composition and found that the mean ratings from older subjects were nearly identical to those from younger subjects. Flannagan et al. (1989, 1993) and Olson and Sivak (1984) reported that the mean De Boer ratings of older subjects were lower (indicating greater discomfort) than those of younger subjects, whereas Theeuwes et al. (2002) and Tsongos and Schwab (1970) reported the opposite effect of age.

Previous work, therefore, supports the notion that glare recovery is related to the dosage of light exposure under conditions representative of nighttime driving and to the age of the driver, but that subjective impressions of the exposure (i.e., how uncomfortable the exposure makes one) are more related to the instantaneous illuminance produced by the exposure profile, regardless of the driver's age. Since the illuminance at a driver's eyes from an oncoming vehicle changes as a function of distance from the oncoming vehicle, the illuminance profile from such a vehicle, plotted as a function of time, will not be rectangular, but irregularly shaped, until the oncoming vehicle passes by, at which time the illuminance from the oncoming headlamps will be zero.

The present chapter, therefore, reports the results of a field study of dynamically changing illuminance profiles representative of those experienced by actual vehicles in meeting situations. The study addresses several of the same basic research questions as those investigated by Van Derlofske et al. (2005):

- Are visual recovery times related to the illuminance received at the eye by oncoming headlamps, by the duration of exposure, or by the dosage of exposure?
- Are subjective impressions of discomfort following exposure to headlamp illumination related to the illuminance received at the eye by oncoming headlamps, by the duration of exposure, or by the dosage of exposure?

Because the present study involved participants from different age groups, the study addresses two additional questions not investigated in previous research on visual recovery in this context:

- Do older drivers experience longer recovery times than younger drivers, following exposure to oncoming headlamp illumination?
- Do older drivers report greater impressions of discomfort than younger drivers following exposure to oncoming headlamp illumination?

Subsequent sections below outline the methods and results of a field study to address these research questions.

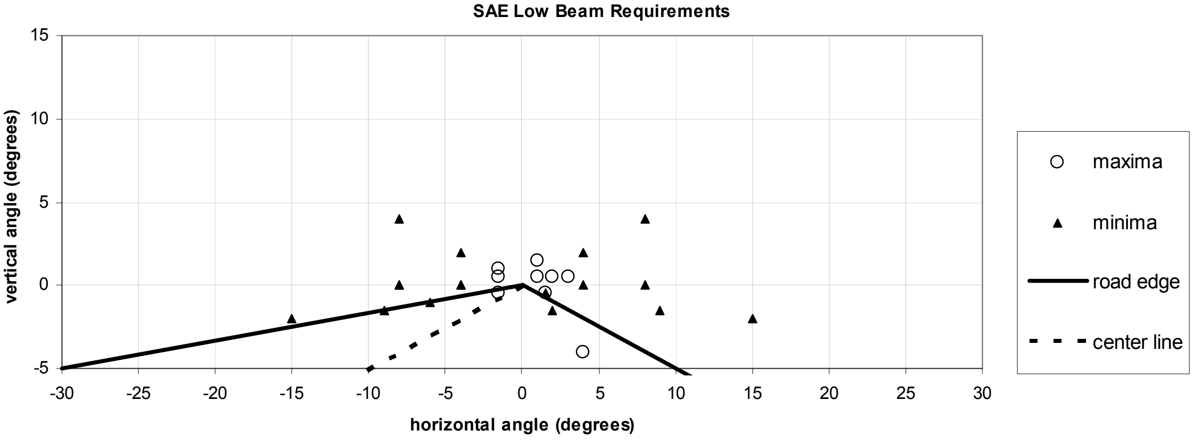


__Figure VI-1.__ Location of several photometric test points (maxima and minima) stipulated by FMVSS 108, superimposed onto a roadway scene.

The study of visual recovery and a potential role of dosage is relevant because present photometric requirements (i.e., Federal Motor Vehicle Safety Standard 108) for headlamps restrict the maximum or minimum luminous intensity produced by headlamps at particular discrete locations (e.g., Figure VI-1). If dosage is an important factor in considerations of visual recovery then such requirements might not address this driver performance issue. Therefore, a discussion of the relevance of present photometric requirements is included.

Methods

Experimental Setting

The field study was conducted outdoors on a paved asphalt surface (reflectance ~10%). Figure VI-2 shows a plan view of the experimental setup. Subjects were seated in the driver's seat of a 1999 Ford Contour. A set of low-beam halogen headlamps conforming to FMVSS 108 requirements for headlamp photometry was placed directly in front of the subjects' test vehicle, aimed to SAE (2002) standards, and operated at 12.8 V during all experimental trials. At a distance of 30 m directly ahead of the test vehicle, a 0.3-m high, seven-segment, red light-emitting-diode display was located, which displayed a random digit (between 0 and 9) at 1-second intervals. Three meters to the left of the display (5° off-axis), a theatrical light projector containing a metal halide lamp was positioned such that it projected a beam of light toward the subjects, in a direction parallel to the subjects' line of sight.

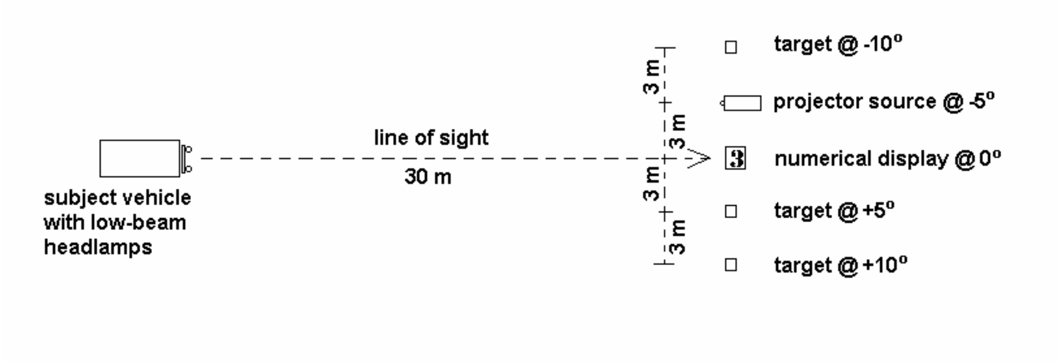


Figure VI-2. *Plan view of experimental layout.*

At locations 6 m to the left, and 3 m and 6 m to the right of the numerical display [10° to the left (-10°), 5° to the right (+5°), and 10° to the right (+10°) of the display], targets consisting of square flip-dot arrays (10 cm by 10 cm) were located. The flip dots on the targets were black on one side and white on the other and could be "flipped" from black to white via a mechanical relay switch (approximate time to flip was 20 ms). The average reflectance of the flip-dot array was 40%; a sheet of glass (transmission ~70%) was positioned in front of each target so that the apparent reflectance of the target was 20 percent. The vertical illuminances on the targets at -10°, +5° and +10° were 3, 14 and 8 lx, respectively. The operation of the projector source and targets, and handling of subjects' responses were handled through control of a laptop computer.

Subjects

Eleven subjects participated in the study. Subjects ranged in age from 22 to 60 years, and were divided into two groups: a younger group with a mean age of 25 years, and an older group with a mean age of 55 years.

Experimental Procedure

During the experimental trials, subjects sat in the driver's seat of the test vehicle. They were handed a control box that contained a single button and instructed to look toward the numerical display, while holding the button down on the control box. While they were viewing the display, and at random intervals during each session, a simulated headlamp illuminance profile from the projector source was displayed (described below). Immediately as the illuminance profile completed, a flip-dot target in a random location was activated (flipping from black to white). As soon as subjects detected a target visible in their peripheral field of view, they were instructed to release the button on the control box for about a second and then to hold it down again. If they did not detect a target they were instructed to keep holding the button down.

Also after each illuminance profile was presented, an experimenter asked subjects to rate their visual discomfort from the lighting condition on the De Boer (1967) scale (where 1=unbearable and 9=just noticeable) and recorded the responses.

After several seconds passed, another illuminance profile would be presented and subjects would respond if and when they saw a target in the scene by temporarily releasing the button. There were four different illuminance profiles used; each was shown followed by the onset of a different target location in a randomized order, each was also displayed with no target onset to check for "false positive" responses (releasing the button with no target present). Thus, each subject experienced a total of 16 illuminance profile trials [4 profiles × (3 target locations + 1 no target) = 16 trials].

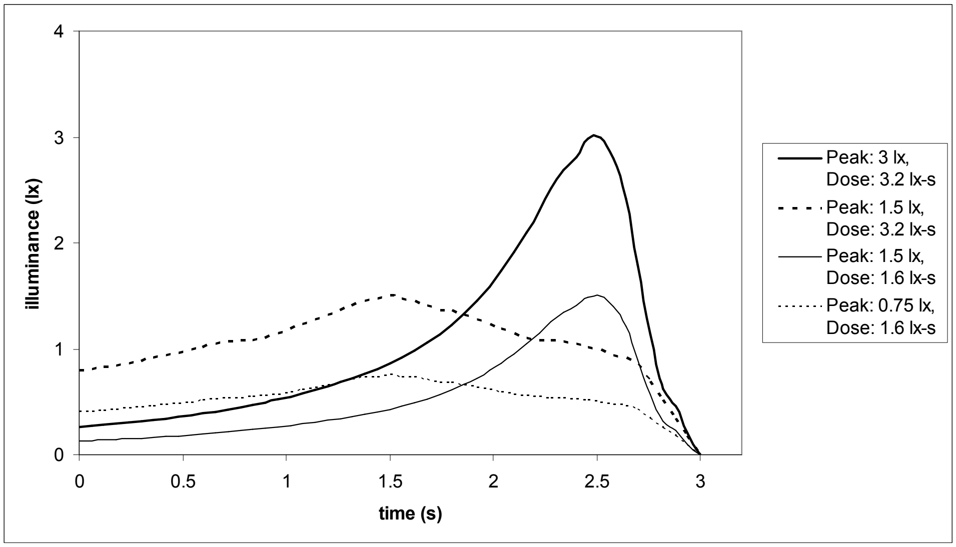


Figure VI-3. *Illuminance profiles used in the field study. Two have the same peak illuminance but different dosage values.*

Simulated Headlamp Illuminance Profiles

The simulated headlamp illumination profiles (illustrated in Figure VI-3) were selected from among several calculated by Chen (2004) based on photometric data for existing low-beam headlamp systems. The profile in Figure VI-3 with the highest peak illuminance (3 lx) is representative of the shape of the illuminance profile from an oncoming vehicle along a two-lane highway with properly aimed halogen low-beam headlamps mounted 66 cm above the ground, while both the subject and the oncoming driver were traveling 35 mph (55 km/h). The absolute illuminance values were scaled slightly to achieve a peak illuminance of exactly 3 lx. The dosage from this profile was 3.2 lx·s. Another profile was created with exactly half the illuminance values as the first one, since different headlamps can have similar profile shapes but different peak illuminance values (Chen, 2004). This second profile had a dosage of 1.6 lx·s.

The profile in Figure VI-3 with the lowest peak illuminance (0.75 lx) was representative of an oncoming vehicle (also along a two-lane highway and traveling 35 mph [55 km/h]) with another halogen low-beam headlamp set mounted 66 cm above the ground. The resulting illuminance profile from this set of headlamps was broader but had a lower peak illuminance, representative of mis-aimed headlamps (upward by about 1°). The dosage from this third profile was scaled slightly to have a value of 1.6 lx·s, similar to that of the second profile described above. Finally, a fourth illuminance profile was created with exactly twice the illuminance of the 0.75-lx-peak profile. This fourth profile had a peak illuminance of 1.5 lx and a dosage similar to the first, 3-lx-peak profile (3.2 lx·s). Thus, none of the profiles were associated with specific headlamps, although the range of characteristics (in terms of peak illuminance and dosage) were within the range of profiles that could be produced by oncoming vehicles.

These four profiles, having different peak illuminances and dosages, provided an efficient set of conditions for testing the relative effects of these factors on glare recovery and rated discomfort.

Simulated Headlamp Illumination Exposure Protocol

Control of the simulated headlamp illumination projector source and other equipment was handled through a laptop running customized software that was written using National Instruments' LabView package. The software generated a randomized order of illuminance profile/target conditions based on the experimenters' input (number of targets, number of profiles, and number of repetitions of each combination). The software contained two subroutines which served the following purposes: one for controlling the light source to produce the headlamp illumination profile during a particular experimental trial, and one for measuring and recording subject response times to the flip-dot targets.

The subroutine designed to create the headlamp illumination profile performed the following steps: it acquired a spreadsheet file describing the headlamp illumination profile to be delivered (see Figure VI-3), translated the entries into DMX-512 commands, and issued them to the theatrical light via an RS-232/DMX-512 interface. The spreadsheet contained the values for illuminance (measured at the subject’s eyes) and duration (which refers to the amount of time until an illuminance value is updated). Illuminance was controlled by adjustment of the size of an aperture within the projector source. Short duration times (60 ms) resulted in a profile that very closely approximated the smooth illuminance profiles in Figure VI-3.

Translation of the spreadsheet information into DMX-512 commands took place in several steps. The first stage was converting the illuminance values into DMX-512 compliant format. This conversion was done using a calibrated look-up table specific to the experimental geometry (the calibration is discussed below). The second stage took the converted illuminance data and formed an array of command strings, which were stored until the experimental trial began.

Once the headlamp illumination subroutine had loaded the array of command strings for the selected profile, it began issuing the commands to the DMX-512 interface. The commands were issued one at a time and were refreshed with the next command once the specified duration had been exceeded. The headlamp illumination subroutine continued to issue commands until the last entry in the spreadsheet had been issued. After the duration of the last command was completed, the projector light source was returned to a dark state, and the headlamp illumination subroutine ended.

Immediately upon completion of the headlamp illumination subroutine, the subject-response subroutine launched and issued the target controller (a separate microprocessor that can measure response times with 1-ms accuracy) the command to activate a specified target (the order of which was determined randomly). The controller changed the state of that target (from black to white) and waited for the subject to release the button on the control box, indicating that the target was detected. The controller then reported the response time to the subject-response subroutine and returned the target to a black state. The response time, along with the profile and target number, were recorded. If the response time exceeded 10 s, the trial was recorded as a "miss." The subroutine then ended.

If more illuminance profile/target combinations remained, the software would continue to launch the headlamp illumination and subject-response subroutines until no combinations remained. When no more combinations remained, the software prompted the experimenter to choose whether to save or discard the collected data.

The process of calibration was handled by separate software and was performed each time the experiment was setup to eliminate errors caused by variations in the light source's position or in the test vehicle position. The calibration software stepped through each of the DMX-512 light levels one at a time and required an experimenter to measure and enter the illuminance of each level (as measured at the subjects' eye level inside the test vehicle). After the maximum required illuminance was measured and recorded, the calibration software was stopped and a calibration file was created from the resulting values.

Results

The results of the study are organized to address the research questions outlined in the Introduction section: what factor(s) affect recovery time, what factor(s) affect discomfort ratings, and how are these responses affected by age?

Recovery Time

Figure VI-4 shows the mean recovery times for each target location, collapsed across all of the illuminance profiles. As might be expected, recovery times for the most peripheral targets were longest. This is caused by a combination of their off-axis location (targets further off-axis are more difficult to detect) and by the lower illuminances on targets that are located more peripherally, a characteristic of most low-beam headlamp patterns such as those used in front of the test vehicle.

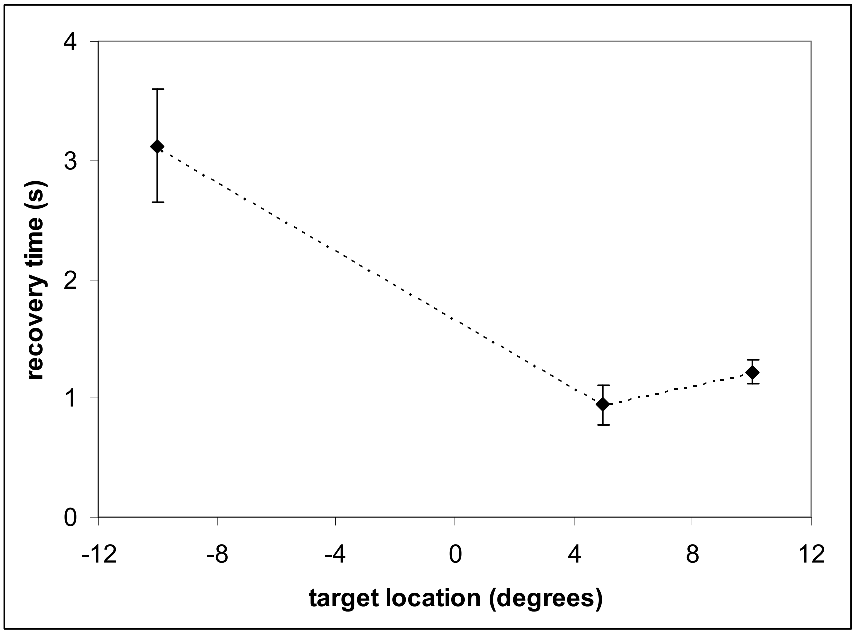


Figure VI-4. *Mean recovery times (±s.e.m.) for different target locations, collapsed all other factors.*

According to the results of a within-subjects analysis of variance (ANOVA), the target location (which also varied with the illuminance on the target) had a statistically significant ($p<0.01$) effect on recovery times.

The same ANOVA revealed that the dosage (1.6 lx·s or 3.2 lx·s) also had a statistically significant ($p<0.05$) effect on recovery times. The two conditions with the higher dosage (3.2 lx·s) resulted in longer recovery times than those with the lower dosage (1.6 lx·s), as illustrated in Figure VI-5. The shape of the profile did not reliably impact recovery times. The recovery times for the two profiles having a dosage of 1.6 lx·s were not reliably different from each other ($p>0.05$); neither were the two profiles with the higher dosage (3.2 lx·s).

Of interest, there was a statistically significant ($p<0.01$) interaction between the target location and the dosage in terms of recovery times, as illustrated in Figure VI-6. For the two targets in the right-hand side of the scene as viewed by the subjects (the +5° and +10° targets), there was little impact of the dosage on response times. But for the leftmost target (at -10°), the response times following the 3.2 lx·s dosage profiles were approximately double those following the 1.6 lx·s dosage profiles (~4 s for the former, versus ~2 s for the latter as shown in Figure VI-6).

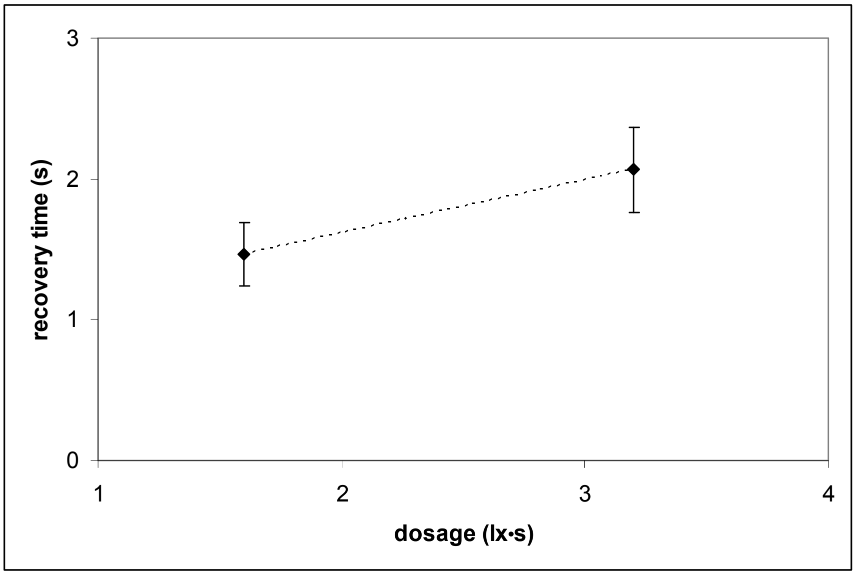


Figure VI-5. *Mean recovery times (±s.e.m.) for the two different dosage conditions, collapsed across all other factors.*

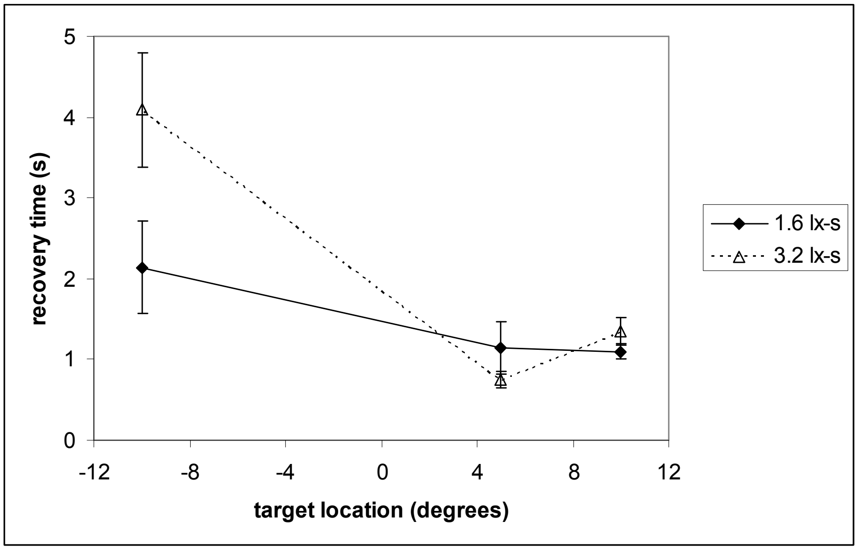


Figure VI-6. *Mean recovery times (±s.e.m.) for each dosage and target location.*

The effect of age was investigated by comparing the recovery times for the older subjects (mean age >50 years) with those from the younger subjects (mean age <50 years) using a between-subjects ANOVA. As suggested by the results shown in Figure VI-7, the older subjects had statistically significantly ($p<0.05$) longer recovery times than the younger subjects.

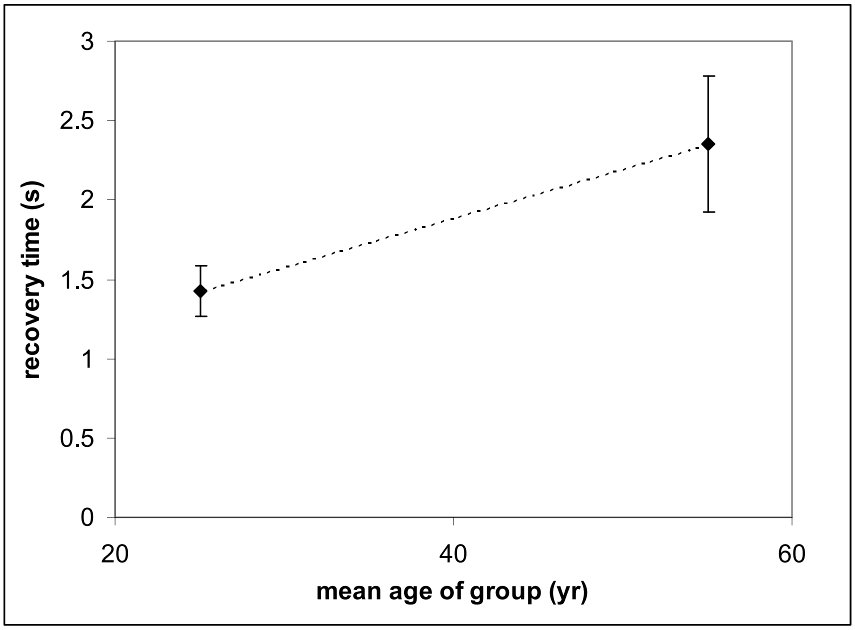


Figure VI-7. *Mean recovery times (±s.e.m.) for each age group, collapsed across all other factors.*

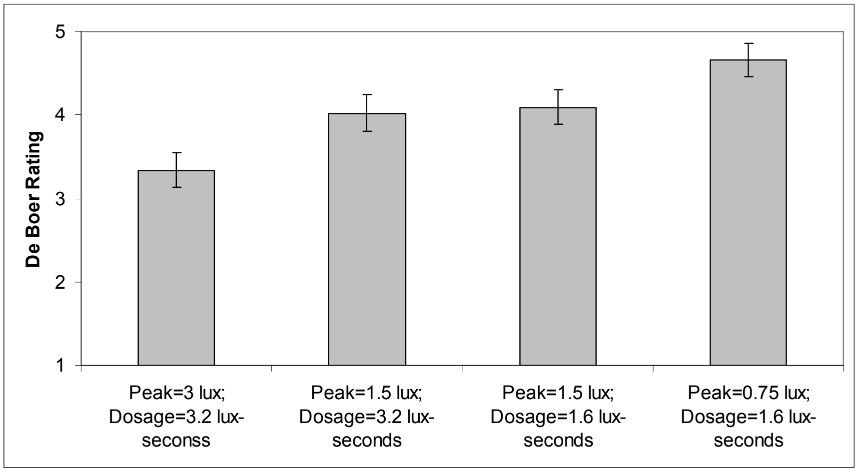


Figure VI-8. *Mean discomfort ratings (±s.e.m.) to each oncoming illuminance profile.*

Discomfort Ratings

Of the four simulated headlamp illumination profiles used in the field experiment, two dosages were represented (1.6 and 3.2 lx·s), and three peak illuminances (0.5, 1.5 and 3 lx). Figure VI-8 shows the discomfort ratings for each of the profiles. A one-way, within-subjects ANOVA conducted on the ratings for each of the four illuminance profiles revealed that there were reliable differences ($p<0.05$) among the conditions. However, subsequent comparisons between the two conditions having a peak illuminance of 1.5 lx revealed that the discomfort ratings for these conditions were not reliably different ($p>0.05$). These results indicate that the peak illuminance, rather than the dosage, was the primary factor associated with rated discomfort.

Nor was there a reliable influence of age on rated discomfort. The mean ratings for the younger (<50 years) subjects were slightly lower (3.9) than those for the older subjects (4.3). However, a between-subjects ANOVA revealed that this difference was not statistically significant (p>0.05).

Discussion

Role of Peak Illuminance and Dosage

As discussed above, the present study was conducted to address the following research questions:

- Are visual recovery times related to the illuminance received at the eye by oncoming headlamps, by the duration of exposure, or by the dosage of exposure?
- Are subjective impressions of discomfort following exposure to headlamp illumination related to the illuminance received at the eye by oncoming headlamps, by the duration of exposure, or by the dosage of exposure?
- Do older drivers experience longer recovery times than younger drivers, following exposure to oncoming headlamp illumination?
- Do older drivers report greater impressions of discomfort than younger drivers following exposure to oncoming headlamp illumination?

Regarding the first two questions, the results support the inference that dosage is the primary factor impacting recovery times following exposure to oncoming headlamp illumination, but that subjective impressions of that illumination is dependent more upon the peak illuminance experienced during that exposure than by the dosage. Thus, these results are consistent with an earlier laboratory study (Van Derlofske et al., 2005) in revealing that glare recovery and discomfort are affected by different aspects of oncoming headlamp exposure. Unlike the previous study, the present study used simulated headlamp illumination profiles that changed dynamically in terms of the illuminance at subjects' eyes. The present results indicate that the relative impacts of dosage and peak illuminance are as found by Van Derlofske et al. (2005), at least for oncoming headlamp illuminance profiles with durations on the order of a few seconds as those in Figure VI-2 are.

It is important also to note that the results of these studies taken together suggest that drivers are not consciously aware of the potential for oncoming headlamps to degrade visibility after they have passed by in the field of view.

Implications for Photometric Requirements

Figure VI-9 shows the same photometric points addressed by FMVSS 108 as illustrated in Figure VI-1. Also illustrated in Figure VI-9 is the angular location (from the headlamps) of an oncoming driver's eyes as the two vehicles pass each other, assuming an oncoming driver eye height of 4 ft, an oncoming driver eye location 4 ft to the left of the roadway center line, and a headlamp height of 26 inches. A couple of the maximum luminous intensity values from headlamps lie close to the curve that is formed by the locations of an oncoming, but much of the oncoming driver-eye curve is not close to any specified maximum luminous intensity location.

One countermeasure for limiting the impact on glare recovery time would therefore involve limiting the total integrated luminous intensity at a series of points along the curve in Figure VI-9. Of course, that curve applies only to the specific assumptions regarding roadway, vehicle and oncoming driver-eye geometry (e.g., flat, straight roadways and the relevant dimensions as listed previously in this paragraph).

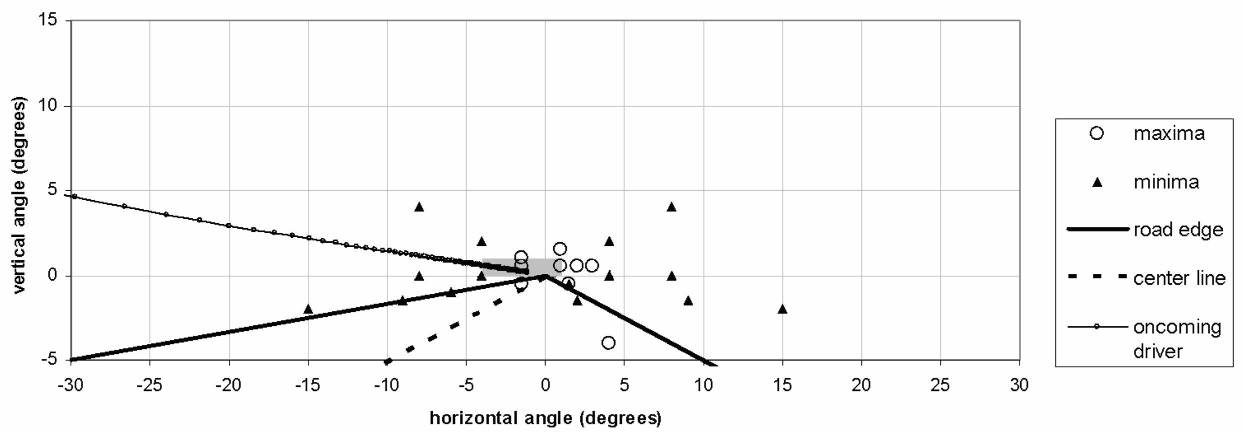


Figure VI-9. *Location of several FMVSS 108 test photometric points (minima and maxima) superimposed over a roadway image. Also shown is a typical location for an oncoming driver's eyes as the vehicle passes by.*

To address the variations in roadway geometry and topography that might be found in real-world conditions, data such as those published by Bhise et al. (1984) might be useful. A set of oncoming driver eye location data was used by Bhise et al. (1984) in the evaluation of headlamp systems for forward visibility and glare. A concentration of these locations is found in an angular region corresponding to a vertical range between 0° and 1° up from horizontal, and between 4° to the left and 1° to the right of center. Extending this angular region along the same direction as the initial driver eye curve results in the angular region shown in gray shading in Figure VI-9. Control of the *sum* of the luminous intensity values in this angular region could help control the illuminance *dosage* experienced by oncoming drivers. Measurement of the luminous intensity at the angular locations within the shaded area would, however, add complexity of the photometric measurements needed to characterize a headlamp.

It has been argued that because the angular position of an oncoming driver's eyes moves away from the geometric origin that the potential for glare recovery diminishes as an oncoming vehicle approaches a pair of headlamps on the road, and this argument is not without merit. If a driver is looking straight ahead, the calculated veiling luminance is reduced as the position of a light source moves toward the periphery (Fry, 1954). This argument, however, is tempered by the fact that oncoming headlamps, particularly in dark environments, are often the only visual information accessible to a driver regarding the relative location and distance of the oncoming vehicle. Drivers make several visual fixations onto oncoming headlamps when driving at night (Aktan and Schnell, 2003), effectively reducing the visual angle between their line of sight and the oncoming headlamps to zero. Thus, the effect of the illuminance/location profile of oncoming vehicle headlamps is not yet precisely understood, but using a location close to the line of sight as in the present study is probably close to a "worst-case" scenario for quantifying the effects of headlamp illumination on glare recovery.

Other Potential Countermeasures

As described above, keeping the line of sight as far away from a light source as possible is one way to reduce its negative impacts. Driver education to use visual cues such as the right-side roadway edge to maintain lane position would presumably help do so, as long as drivers still maintain some visual contact with the entire scene in order to respond to potential hazards. A shaded visor or that could be located along the interior of one's windshield might be another suitable countermeasure for reducing the dosage experienced from oncoming headlamps. Such a device would not have to be large, and could consist of a narrow rectangle, perhaps 2 to 5 cm in width and 5 to 10 cm in length so as to reduce the illuminance from a small angular portion through the windshield. Drivers might be able to position their heads in order to superimpose the visor between their eyes and oncoming headlamps. Even if its transmittance were 50 percent, the reduction in recovery times might be beneficial. Of course, such a solution would result in reduced apparent luminance of the forward scene in that angular region, but with regular head movement, drivers could learn to look around such a device (or to retract it when oncoming vehicles are not present). Obviously, considerable research would be needed before such a device could be validated as both useful and safe, but it could provide a means for mitigating the dosages experienced from oncoming headlamps.

VII. OVERALL CONCLUSIONS

The overall findings of the studies presented in this report and in the accompanying reports associated with NHTSA's research program on forward lighting and glare (NHTSA, 2007; Akashi et al., 2008; Bullough et al., 2008) have used disparate methodologies and in some cases, novel or exploratory measurement techniques and analyses. As cautioned several times in the present report, the conclusions from this series of studies are sometimes tentative or preliminary, and as with most research studies, they do not close the book on the causes of and countermeasures for headlamp glare. Nonetheless, the studies described herein do provide some insight regarding why thousands of members of the driving public have contacted NHTSA with their concerns about glare.

As described in NHTSA's (2007) initial report to Congress on headlamp glare, there is no single cause of glare that can be isolated and eliminated. Vehicle design (e.g., higher proportions of trucks/SUVs), lighting technologies (e.g., HID light sources), headlamp maintenance practices (e.g., periodic aim inspection) and even driver demographics (e.g., older drivers) have all evolved in the past two decades. The proportion of older drivers on roadways will increase; additionally, it is likely that there will always be unlighted, two-lane highways on which the effects of headlamp glare are greater than on other types of roadways. And even if the results of the pilot study described in this report to determine whether stronger links between headlamp glare and safety are tentative and incomplete, evidence suggesting that headlamp glare is an important safety issue exists. What can be done, then, to reduce the effects of headlamp glare?

Given the influence of headlamp aim on measures of visibility and glare (Akashi et al., 2008), and the frequency of mis-aim found on vehicles, more consistent vertical aim of headlamps would provide more consistent light levels toward oncoming drivers' eyes, and reduced instances where light levels are high. Periodic adjustment of headlamp aim or automatic adjustment systems could then be helpful countermeasures against glare.

The visual needs survey tended to point to the basic conclusion that low beam headlamp beam patterns are, if not perfect, then close to optimal given their attention to controlling glare. Even though higher intensities from such headlamp patterns are probably necessary to ensure detection distances sufficient to respond to hazards at many driving speeds, drivers' intolerance for the discomfort glare from such intensities probably limits the feasibility of increasing low-beam headlamp intensity significantly. Many lines of evidence suggest that increasing the intensity of a headlamp will improve visibility for a driver and simultaneously worsen glare for other drivers.

Adaptive headlamp systems such as the SAFS prototype evaluated through the present research program (Bullough et al., 2008) provide a possible work-around regarding the inherent conflict between visibility and glare by reducing luminous intensity only when and where other drivers are located and maintaining higher intensities for good visibility in the remaining parts of the visual scene. To be sure, such systems could be embodied in many ways other than the system developed in the present research program; for example, light emitting diodes (LEDs) could be a useful light source technology for dynamically switching or dimming parts of a beam pattern. But the results of the SAFS prototype evaluation appear to show that the basic approach has merit and can be demonstrated on moving vehicles.

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