Countermeasures for Reducing the Effects of Headlight Glare

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Foreword

This study was funded by the AAA Foundation for Traffic Safety. Founded in 1947, the AAA Foundation is a not-for-profit, publicly supported charitable research and educational organization dedicated to saving lives and reducing injuries by preventing traffic crashes.

This peer-reviewed report was created in response to the increasing public interest in the problem of headlight glare. New headlight technology, an aging population, and innovations in vehicle design have all contributed to increased problems with glare. This in-depth, comprehensive report examines the factors that contribute to glare problems and looks at a wide range of possible countermeasures. Although the researchers could not identify any single, simple solution, the report does provide a number of helpful suggestions for countermeasures that can lessen the discomfort and perceived danger caused by headlight glare.

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Countermeasures for Reducing the Effects of Headlight Glare

Prepared for the AAA Foundation for Traffic Safety by Mace, Garvey, Porter, Schwab, and Adrian, published December 2001

Clarification and correction of misleading statements added 12-18-02

p. 31:

This report states that, "Several companies offer halogen bulbs that are coated blue to look like HID bulbs. These bulbs are not legal…." It also states that the "… expensive HID conversions are illegal in the United States."

The foregoing statements are somewhat misleading because they imply that *all* aftermarket products are illegal. In fact, if a manufacturer's aftermarket product, such as a conversion kit, complies with the performance specifications in FMVSS 108, the product is perfectly legal. On the other hand, AAA Foundation research indicates that many aftermarket products that do not meet FMVSS 108 are still being sold, including but not limited to coated bulbs.

p. 31:

"Other conversion kits that use true HID bulbs (usually xenon lights) are available, but they are limited in practice to systems that use single-filament bulbs…."

This statement is incorrect. HID lamps do not have filaments. Instead, they generate visible light using a discharge arc.

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Executive Summary

Driving an automobile is primarily a visual task, and vision contributes as much as 90% of the information needed to drive (Alexander and Lunenfeld 1990). Night-time driving poses a special challenge, since even at night drivers need to be able to see traffic control devices, lane lines, vehicles, pedestrians, animals, and other potential hazards. Artificial lighting can illuminate the roadway, but too much light or improper lighting may result in glare, which causes visual discomfort and a diminished ability to see the environment.

There are only two practical methods for night-time lighting: fixed overhead lighting and vehicle headlights. While the number of roads with fixed overhead lighting increases each year, this form of lighting is expensive and cannot be relied upon as the only means for providing night visibility. From its inception, the use of headlights on automobiles has involved a compromise between providing enough light for drivers to see the road ahead and avoiding the excessive light that produces glare.

Changes in headlamp designs that affect light intensity, beam pattern, and aiming have significantly improved night vision on the highway. Technology has brought changes to headlights, interior surfaces (including mirrors), and the highway environment that directly reduce glare or indirectly reduce the effect of glare on the driver. However, every change has involved a tradeoff with hidden costs. For example, lowering headlamps may reduce glare but can result in a loss of forward visibility.

The framework for all subsequent discussions of glare in roadway lighting was created by Holladay (1926) in the USA and by Stiles (1928 - 29) in the UK. Holladay originated the concept of "disability glare," glare that decreases a driver's ability to see clearly. Stiles showed that disability glare is caused by the scattering of light in the optic media of the eye, rather than occurring in the optical nerve, as Holladay had assumed. Holladay acknowledged Stile's explanation but noted that it did not explain all of glare's effects. This exchange apparently began the present distinction between disability glare and discomfort glare.

This report provides the reader with a working knowledge of glare and the methods used to measure and control glare. It is a rather technical report aimed at engineers and experts in lighting and traffic safety.

Glare occurs when visual field brightness is greater than the luminance to which the eyes are adapted. It can be caused by direct and indirect light sources. Discomfort glare causes discomfort, annoyance, fatigue, and pain. Disability glare produces a reduction in the visibility distance of low-contrast objects. The elderly, people with light-colored eyes, and those suffering from cataracts are especially sensitive to disability glare. Glare at night can be mitigated by design changes in roadways, automobiles, and vehicle lighting systems.

Countermeasures work in four ways, by:

1) Reducing the intensity of the glare source;
2) Reducing the illumination reaching the driver's eyes;
3) Increasing the glare angle; and
4) Indirectly minimizing the effects of glare.

Some glare countermeasures may require federal rulemaking, while others can be implemented by highway agencies, vehicle manufacturers, and motorists.

Countermeasures requiring government involvement include:

- Enforcement of headlight aim standards
- Changes in beam photometric distribution
- Ultraviolet headlights
- Polarized headlights

Some 50 percent of vehicles have their headlights misaimed and the problem increases as the vehicle ages. Because misaim magnifies all other problems with the low-beam photometric pattern, misaim is clearly the place to begin finding effective countermeasures. In addition, since public complaints seem to be mostly about glare from newer vehicles, headlamp aim in vehicles with HID lamps would be a logical place to apply corrective solutions.

Federal rulemaking is required to make any major modifications to the low-beam photometric distribution. Every effort to reduce headlamp illumination or change the beam pattern has been met with concern about visibility, and every effort to increase illumination has been met with concern about glare. Research does not support change in either direction or use of the current beam pattern. The present standard is a compromise that has evolved over time and works reasonably well; the risks of making any major change appear too great. Therefore, any effort to develop countermeasures for glare should focus on one or more of the other alternatives discussed in this report.

Ultraviolet lighting has some potential to reduce headlight glare, but only indirectly. This technology should and will be pursued primarily because of its benefits to vision, particularly vision under adverse conditions such as rain, snow, and fog, but it is not likely to replace conventional lighting and so cannot offer a realistic countermeasure to glare.

Of all the countermeasures discussed in this report, polarized lighting is the one that could eliminate glare entirely and make the nighttime road a friendlier place to travel. With the advent of HID lamps, the very technology that has heightened the glare problem offers the best ultimate solution. With polarized lighting, the tradeoff between visibility and glare is resolved. The only real obstacle to pursuing this countermeasure further is the difficulty of implementation.

Countermeasures that can only be initiated by a highway agency include the following:

- Wide medians and independent alignment
- Glare screens
- Fixed roadway lighting

Wide medians, independent alignment, and glare screens are all effective in eliminating glare from oncoming vehicles, either by increasing the glare angle so that its effect is reduced or by blocking glare illumination completely. Wide medians and independent alignment are used primarily in rural and suburban areas, where a wide right-of-way is available, while glare screens are used primarily in urban areas, where the right-of-way is narrower. Wide medians and independent alignment are part of the design process and generally cannot be added after construction. Glare screens are a remedial treatment and can be installed when the initial design does not allow sufficient right-of-way for a wide median or when traffic volume increases and glare problems grow worse. Practical limits on height restrict the use of glare screens to roadways that are relatively flat and have gentle curves. Since the screens' effect on crashes is not documented, the cost must be justified by issues of comfort and possible safety benefits.

Like wide medians and independent alignment, fixed roadway lighting is often justifiable on the basis of crash reduction alone. However, fixed lighting requires access to electrical power and is generally restricted to urban areas. Installation of fixed lighting also depends on budgets and reflects varying criteria used by highway agencies. The question of whether low-volume roads should be illuminated to minimize glare is not easily answered. Drivers are certainly more comfortable driving on illuminated roads, and this benefit alone might justify lighting more roads. However, this should be a local decision, made with an understanding of local resources and priorities.

It is unlikely that all roads with glare problems will ever be illuminated, so other solutions must be found. A variety of road improvements, including alignment, lane width, surface markings, and so on, may reduce the discomfort experienced from headlight glare.

Countermeasures that are primarily the responsibility of industry are:

- Headlamp height
- Color-corrected headlamps
- Headlamp area
- Adaptive headlamps

Of these four countermeasures, limiting headlamp height is the only one that could be implemented quickly and with minimal cost. Lowering headlamp height is a promising "no cost" countermeasure to glare, but its impact is limited to mirror glare. With light trucks (pickups, full-size vans, and sport-utility vehicles) representing 50% of all vehicle sales, lowering the headlamp height of these vehicles should be pursued. Lower headlamp height on large trucks may be more problematic, given visibility concerns.

Color-corrected headlamps, while offering a low-cost solution, require a significant amount of additional research before adoption.

Headlamp area is related to glare discomfort, with larger headlamp size causing less discomfort. Projector-style HID headlamps may be contributing to discomfort glare because their surface area is smaller than standard headlamps and so their luminance is much higher.

Adaptive headlamps, while theoretically promising, have numerous design, cost, and regulatory obstacles that need to be surmounted. While it is clear that adaptive headlamps offer significant improvements to visibility, for example on curves, it is not at all certain what their effect would be on glare. Cost and maintenance issues also need to be resolved before adaptive headlighting becomes a practical countermeasure to glare.

Countermeasures that are under the control of motorists are:

- Reduced night driving
- Night-driving glasses
- Anti-glare mirrors
- Corrective vision solutions

Drivers who are especially bothered by nighttime glare should try to reduce their exposure to it by driving less at night. Scratched or dirty eyeglasses and damaged contact lenses make the problem even worse. Glare-sensitive drivers who must drive at night should learn coping strategies by taking a driver improvement course, such as those offered by AAA, AARP, and the National Safety Council.

Research shows that, for most individuals, night-driving glasses are not an effective countermeasure. While discomfort is reduced, so is visibility. This conclusion applies to both full eyeglasses and half-glass analyzers that allow the driver to look through the analyzer only on demand. Although one study suggested that discomfort glare had little effect on driving performance, the measurements of performance were entirely psychomotor and not visual. Research is needed to understand the relationship, if any, between discomfort and performance. Although we know how driving affects perceptions of discomfort, we do not know how discomfort glare affects eye fixations, attention, and fatigue. There is research that suggests that drivers' eyes are attracted to light but are drawn away from glare sources. Additional research is needed to support or reject the assumptions being made and the conclusion that night-driving glasses (including half-glass analyzers) have no value for anyone driving at night.

Anti-glare mirrors, together with limits on headlamp height and enforcement of standards for headlight aiming, are all that is needed to control mirror glare from passing or following vehicles. Until all vehicles are equipped with some type of automatic glare-reduction mirrors in both the rear-view and left side positions, drivers need to be encouraged to use the night setting of their interior mirrors and to aim the left outside mirror so that it does not reflect directly into their eyes. The question of what drivers need to see in their rear-view mirrors needs further study so that automatic glare reduction mirrors can be properly designed.

Vision correction should be strongly encouraged for safety reasons, but provides only a minimal reduction in glare.

While one might think that maintenance of headlamp aim is a countermeasure drivers could implement, there is generally little incentive to do so. Drivers will correct their misaimed headlamps only when their own ability to see is compromised, and this situation usually does not create a glare problem. If misaimed headlamps do cause glare, the driver is likely to think they are fine, because for the driver increased glare also means improved visibility. Misaimed headlamps are the most problematic source of headlight glare, since correcting them requires the uniform enforcement of headlamp aiming standards.

Two of the potential countermeasures discussed in this report are being studied in large ongoing research programs. Adaptive headlamp technology is being developed and strategies for its implementation are being devised with the support of several European countries and manufacturing firms. In the U.S., a comprehensive research program for the development and implementation of UVA headlamps is underway. Both adaptive headlighting and UVA headlamps are more likely to benefit visibility than to offer any comprehensive solution to headlight glare.

Topics that should be investigated include polarized lighting; the effects of the spectral content of light on visibility and discomfort at mesopic adaptation levels; the relative effectiveness of electrochromic, photochromic and neodymium mirrors on glare sensation and rearward visibility; the identification of the population of drivers most affected by glare and the reasons for their problems with headlight glare; and a more complete description of the behavioral effects of discomfort glare.

CHAPTER 1
INTRODUCTION

Driving an automobile is primarily a visual task. By one estimate, as much as 90% of the information that drivers gather is received visually (Alexander, G. and Lunenfeld, H. 1990), and whatever the actual percentage may be, the importance of the visual system to driving can not be doubted (Sivak, 1996). However, in order for the visual system to detect, attend to, and recognize information, there must be adequate lighting. Drivers require enough lighting at night to see a variety of objects on the highway, including traffic control devices, lane lines, vehicles, pedestrians, animals, and other potentially hazardous objects. However, too much light or improper lighting can result in glare, which can be a major problem both in terms of the ability to see and visual comfort.

There are only two practical methods of lighting the highway system at night: fixed overhead lighting and vehicle head lighting. While the fraction of roads with fixed overhead lighting increases significantly each year, this form of lighting is expensive and can not be relied upon as the only means of providing for night visibility. Head lighting, from its inception, has involved a compromise between providing sufficient lighting for drivers to see (with adequate preview time), and avoiding excessive light that might produce glare. These two goals have been translated into standards in the form of minimum requirements to provide visibility and maximum limitations to control glare.

Progressive improvements in headlighting and new technologies have increased night visibility and reduced the impact of glare, but any changes should be carefully considered before implementation. Changes in headlamp designs that affect light intensity, beam pattern and aiming have significantly improved night vision on the highway. Along with improvements in headlight systems, glare resistant interior surfaces, glare-reducing mirrors, and changes to the highway environment have either directly reduced glare or indirectly reduced the effect of glare on drivers. However, every change has involved a tradeoff with hidden costs. For example, lowering headlamp mounting heights has a minimal monetary cost, but this change may result in a loss of forward visibility; making other changes, such as installing dynamic headlight aiming systems, may be very costly. To best manage such costs, it is necessary to have a good understanding of the glare problem and of the importance of various aspects of the problem. Otherwise, the old adage, “be careful what you ask for, because you might get it,” could apply.

Research on glare has a long history, marked by the competing perspectives of researchers in an international community. The seminal work, setting the framework for all subsequent discussions of glare in roadway lighting, was done by Holladay (1926) in the USA and by Stiles (1928–-29) in the UK. Holladay is the acknowledged originator of the concept of what is now known as disability glare, the glare that results in a loss of visibility. Stiles showed that disability glare is caused by the scattering of light in the optic media of the eye, rather than cross-talk in the optical nerve, as Holladay had assumed. Holladay acknowledged Stile’s explanation to be true, but noted that such scattering did not explain all of glare’s effects. This exchange was apparently the beginning of the present distinction in glare research between disability glare and discomfort glare. Whereas disability glare impairs the eye’s ability to distinguish small changes in brightness, discomfort glare results in discomfort, sometimes causes fatigue, and may even produce pain.

The purpose of this report is to provide the reader with a working knowledge of glare and of the methods that may be used to measure and control glare's effects. In Chapter 2, the two types of glare are defined and key factors are identified that contribute to each, based on the most recent scientific research. This information is essential for understanding the potential effects of proposed countermeasures to glare. Chapter 3 discusses how headlight glare impacts night driving. That discussion should help in making an accurate assessment of the extent of the glare problem and so help determine whether the inevitable cost of a proposed countermeasure is worthwhile—are the negative effects of headlight glare so bad that their resolution can justify the efforts required? Chapter 4 contains a discussion of the source of glare in the driving environment and a comprehensive review of glare countermeasures. Chapters 5 through 8 describe specific types of potential countermeasures, explaining why each countermeasure is thought to be effective, giving a review of the relevant research (including the extent to which each countermeasure has been tested or implemented), and rendering a judgement about whether the countermeasure has been shown to be effective or could be effective—or, if not effective, what would be necessary to successfully implement the countermeasure. Finally, Chapter 9 presents conclusions concerning what countermeasures may be cost-effective and where additional research seems warranted.

The remainder of the introduction provides definitions of some basic terms used in the study of lighting and vision. The key terms to be defined are:

- Brightness
- Point light source
- Luminous intensity
- Luminance
- Illuminance
- Reflectance
- Glare

Brightness is the attribute of visual sensation according to which an area appears to emit more or less light. Brightness is a relative term which describes the appearance of an object to an observer. An object of any brightness will appear brighter if the ambient light levels are lower. Brightness can range from very bright (brilliant) to very dim (dark). In popular usage, the term "brightness" implies higher light intensities, whereas "dimness" implies lower intensities.

Point light source is a light source that subtends an extremely small angle at the observer's eye so that its attributes are not affected by its size, only by its luminous intensity. An example of a point light source is a star.

Luminous intensity is the light-producing power of a source, measured as the luminous flux per unit solid angle in a given direction. It is simply a measure of the strength of the visible light given off by a point source of light in a specific direction, and usually expressed in terms of candelas (cd), where one cd equals one lumen/steradian.

Luminance is the amount of luminous flux reflected or transmitted by a surface into a solid angle per unit of area perpendicular to given direction. More simply, it is a physical measure of the amount of light reflected or emitted from a surface and roughly corresponds to the subjective impression of "brightness." Luminance does not vary with distance. It may be computed by dividing the luminous intensity by the source area, or by multiplying illuminance and reflectance. The most common units of measurement for luminance are candelas per square meter (cd/m^2), foot-lamberts (fL), and millilamberts (mL).

Illuminance is the photometric flux (or, more simply, the amount of light) incident per unit area of a surface at any given point on the surface. The illuminance E at a surface is related to the luminous intensity I of a source by the inverse square law $E=I/d^2$, where d is the distance between the source and the surface. The most commonly used units of measurement for illuminance are lux (lumens per square meter) and foot-candles (fc, or lumens per square foot). Retinal illuminance is the amount of photometric flux that reaches the retina of the eye; it is a function of the diameter of the pupil of the eye and the amount of light absorption within the eye. The unit of measure for retinal illuminance is the troland (Td), which is defined without regard for the absorption in the eye. A nominal retinal illuminance of 1 Td is experienced by an observer looking at a surface of luminance 1 cd/m^2 through a pupil area of 1 mm^2.

Reflectance is a measure of the reflected incident light (illuminance) that is actually reflected away from a surface. For many surfaces reflectance will depend on the angle of viewing and the angle from which it is illuminated, as well as the properties of the surface (including diffuseness or retroreflectivity of the surface).

Glare can be defined generally as a bright, steady, dazzling light or brilliant reflection that occurs when the luminous intensity or luminance within the visual field is greater than that to which the eyes are accustomed. Glare can cause discomfort, annoyance, or loss in visual performance and visibility. Direct glare is caused by light sources in the field of view whereas reflected glare is caused by bright reflections from polished or glossy surfaces that are reflected toward an individual (for example, a chrome nameplate on a leading vehicle). The entire visual field contributes to the glare level, and even a completely uniform field, such as that in a photometric sphere, will produce some glare. Detailed discussion of the factors that contribute to glare will be presented in Chapter 2.

Summary

Glare occurs when visual field brightness is greater than the luminance to which the eyes are adapted. Glare is caused by both direct and indirect light sources. Discomfort glare produces visual discomfort, annoyance, and fatigue. Disability glare produces loss in visual performance which is generally defined as a reduction in the visibility distance of low contrast objects. The elderly, people with light-colored eyes, and those suffering from cataracts are especially sensitive to disability glare. Glare at night can be mitigated by prudent design of the roadway, the automobile, and vehicle lighting systems.

CHAPTER 2
FACTORS THAT CONTRIBUTE TO HEADLIGHT GLARE AT NIGHT

To critically evaluate the potential effectiveness of any glare countermeasure, it is essential to understand the physiology of glare and its causative factors. Glare is usually classified according to its effect on an observer, but each type of glare has its own physiological explanation.

The two principal types of glare are disability glare and discomfort glare. Disability glare impairs the capability of the eye to perceive small changes in brightness (such as the luminance of the object to be seen), while discomfort glare, as its name implies, creates an uncomfortable sensation. There is a tradeoff between visibility and glare; for example, research (Hemion 1969a and Flannagan 1996) indicates that visibility is improved when opposing vehicles both use high beams, although this creates discomfort glare. The automotive headlighting industry has always felt that discomfort glare was more important than disability glare, because discomfort glare is what drivers complain about.[1] However, disability glare may be equally important, because it is directly related to the driver's ability to see objects and thus may be more likely to result in crashes.

Generally, glare results from a bright, steady, dazzling light or its reflection from shiny surfaces; it occurs when the luminous intensity or luminance within the visual field is considerably greater than that to which the eyes are adapted. Direct glare is caused by light sources in the field of view (such as headlights, taillights, and luminaires). Reflected glare is caused by specular reflections from polished or glossy surfaces such as the steel or aluminum doors on tractor trailers, a rear-view mirror at night, or even bright matte surfaces, such as vehicle interiors and dashboards, that reflect light toward the driver.

Glare affects both day and night driving performance. During the day, sunlight produces direct glare and gives rise to indirect glare from surface reflections. At night, automobile headlights produce direct glare by shining into the eyes of drivers in approaching cars, and indirect glare is experienced from rearview mirrors and vehicle interiors that reflect light from trailing vehicles. The effects of glare on drivers are much greater at night than during the day, because at night drivers are adapted to lower light levels and so require a greater difference in luminance between objects and background to perceive objects on the road. This luminance difference is reduced by stray light coming either directly from a glaring light source or indirectly from reflections of headlamps on wet road surfaces, mirrors, or vehicle interiors. Lights that are barely noticeable during daylight can be uncomfortably glaring at night.

Disability and discomfort glare apparently have quite different physiological origins and so are very difficult to compare. Disability glare comes from light scattering in the ocular media, whereas the sensation of discomfort glare appears

[1] *Waltham has expressed the opinion what people sense about glare is discomfort and so it is discomfort on which they base their judgements about glare. At low light levels, one can experience vision impairment before experiencing discomfort. (CIBSE meeting in Bristol U.K., 1963)*

to be related to neuronal interactions similar to such physiological functions as skin resistance or the pupillary response to light (Fry and King 1975). The two types of glare are affected differently by environmental parameters. For example, disability glare does not seem to be affected by source size or luminance, but it is affected by luminous flux and the angular offset from the line of sight. In contrast, for discomfort glare the apparent source luminance and size are major parameters. As long as the size and position of headlights are kept more or less the same, steps taken to reduce discomfort glare will also reduce disability glare. However, if the size of the headlight source is reduced while keeping the emitted flux constant, the higher headlight luminance will increase discomfort while the disability effects will stay the same. This effect may explain the complaints about glare with some high-intensity discharge (HID) lamps, which, on any specific beam angle, project similar illumination as a halogen lamp, but through a smaller opening.

Another consequence of the different behavior of disability and discomfort glare is that when background luminance is low, glare sources may have a disabling effect on vision without being a source of discomfort. This problem has been addressed by using roadway lighting to provide minimum background luminance levels. With sufficient ambient illumination, a glare source may create a discomforting sensation without a measurable disabling effect.

Disability Glare

Disability glare is created by a light so bright that its intensity results in a measurable reduction in a driver's ability to perform visual tasks. The reduction in visual performance is a direct result of the effects of stray light within the eye, which in turn are dependent on the age of the driver. Transient adaptation refers to a temporary reduction in basic visual functions, such as contrast sensitivity and form perception, that occurs when the luminances from objects in the visual field change rapidly (Adrian 1991a). The degree of reduction in function is dependent on the change in luminance to which the eye must adapt. Transient visual impairments are associated with rapid alterations in glare levels and changes in scene luminance, as well as sudden eye movements (or saccades). Glaring light scattered in the eye can be expressed as the superposition of a uniform luminance onto the retinal image. This "veiling" luminance, which is a function of the glare angle (the angle between the line of sight and the glare source), adds to scene luminance and reduces the contrast of the target to be seen. This formula for contrast C without glare is:

1) $C = L_T - L_B / L_B$

where L_B is the background luminance and L_T is the luminance of the object to be seen (the target).

If disability glare (L_{seq}, the equivalent luminance of stray light in the eye) is added to the luminance of both the target and background, the formula for contrast in the presence of glare becomes:

2) $C = [(L_T + L_{seq}) - (L_B + L_{seq})] / (L_B + L_{seq})$
$= (L_T - L_B) / (L_B + L_{seq})$

This formula indicates that contrast will be reduced as L_{seq} is increased.

Visual acuity depends on the contrast between the background and the objects to be seen. The presence of glare reduces the ratio of target contrast to threshold contrast, and the target is less likely to be seen or drowns completely in the light veil.

Direct glare in night-driving encounters has strong angular or spatial dependence, resulting in eye movements that almost invariably lead to transient changes in the luminance reaching the eye and so to either dark adaptation or light adaptation. As part of the adaptation process, the retina adjusts to the quantity of light. Although different parts of the retina are exposed to different quantities of light (for normal scenes of non-uniform luminance), it is generally assumed that an instantaneous state of adaptation of the fovea (the central retinal region) can be described by an equivalent veiling luminance from a uniform source superimposed on the visual field. A given state of foveal adaptation, therefore, can be produced by many luminance configurations.

The principle that the effect of a glare source can be represented by a uniform background luminance was developed by Holladay (1926), who assumed that the glare effect was caused by crosstalk in the optic nerve. Stiles (1928–29) attributed the glare effect to stray light in the eye. Crawford (1936) showed that stray light in the eye from different sources is additive in nature. The equivalent stray light luminance L_{seq} varies with age, and can be calculated according to equation 3, below.

Causes of stray light in the eye include scattering, diffraction on the fringe of the pupil, and optical imperfections in the eye, all of which deflect light from the geometric image on the retina. Added incoherently to the light of the image, stray light reduces the contrast between the image and background. The effects of disability glare also increase with the age of the observer due to changes in the intraocular media and cornea of the aging eye that increase scattering. Adrian (1975) and Ijspeert (1990) found that the glare effect begins to increase rapidly at between age 35 and 40.

Since the work of Holladay in the 1920s, several equations have been proposed to account for the effect of disability glare(see the review by Adrian and Bhanji, 1991). All of the formulas give veiling luminance L_{seq} as a function of the illuminance produced by the glare source, measured at the vertical plane of the driver's eye, and the glare angle, the angle between the object being viewed and the center of the glare source. In general, the formulas are similar, with the primary difference between them being in the exponent used for the glare angle. The formulas have been "fine tuned" by Hartman and Moser (1968), Vos and Padmos (1983), and most recently Adrian and Bhanji (1991) to include the effects of driver age and to improve predictions at small glare angles. The three factors now considered to determine veiling luminance are:

1. Illuminance on the eye from the glare source (E_{gl} in lux) in the plane normal to the line of sight.
2. Angle between the line of sight and the center of the glare source (θ in degrees)
3. Age (in years)

The equation for veiling luminance (L_{seq}) currently accepted by the Illumination Engineering Society of North America was first presented by Adrian and Benji (1991):

3) $L_{seq} = k\sum_{1}^{n}\frac{E_{gli}}{\theta_i^n}$, where

$$k = 9.05\left[1+\left(\frac{\text{age}}{66.4}\right)^4\right]$$

$$n = 2.3 - 0.7\log\theta,\ \text{when } 0.2^\circ < \theta < 2^\circ$$

$$n = 2,\ \text{when } \theta > 2^\circ$$

For night driving, L_{seq} should not exceed 15% of the background luminance L_B, which is usually approximated by the luminance of the pavement.[2] When $L_{seq} / L_B = 0.15$, the visual threshold for detection is increased by approximately 10% for a target subtending10 minutes of arc at a road surface luminance of 1cd/m^2. L_{seq} is most often used to predict the visibility of a specific target in the presence of a given background. The impact of L_{seq} on the visibility of a target subtending10 minutes of arc can be seen in Figure 1.[3] Because disability glare reduces the contrast between target

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[2] *There is no scientific basis for maintaining the ratio of L_{seq} / L_B at a maximum of 0.15, but it is a generally accepted convention.*

[3] *At a distance of 410 feet, the stopping distance at 50 mph, an object 14 inches tall will subtend a visual angle of 10 minutes of arc at the driver's eye. Smaller objects would require greater contrast and larger objects less contrast than predicted by figure 1 in order to maintain visibility.*

and background, the target luminance has to be increased in the presence of glare to render the target visible. The table indicates the amount by which glare (represented by L_{seq}) increases the threshold luminance, which is the contrast between target and background at which 50% of observers would see the target when presented for a brief interval. The threshold increment TI is the percentage by which the threshold luminance is increased; it can be calculated by:

4) TI (in %) = $60.3\ L_{seq}\ /\ L^{0.86}$

where L is the average pavement luminance.

We can see from Figure 1 that when the pavement luminance is about 0.28 cd/m², and L_{seq} is .02 cd/m² (an unlighted road), the threshold contrast must be increased by more than 5% to maintain visibility. However, if the pavement is lighted so that its luminance is more than 0.6 cd/m² , no significant increase in threshold contrast is necessary. On the other hand, if L_{seq} is 0.1 cd/m² or more and the pavement luminance is less than 0.35 cd/m², threshold contrast must be increased by more than15% to maintain visibility.

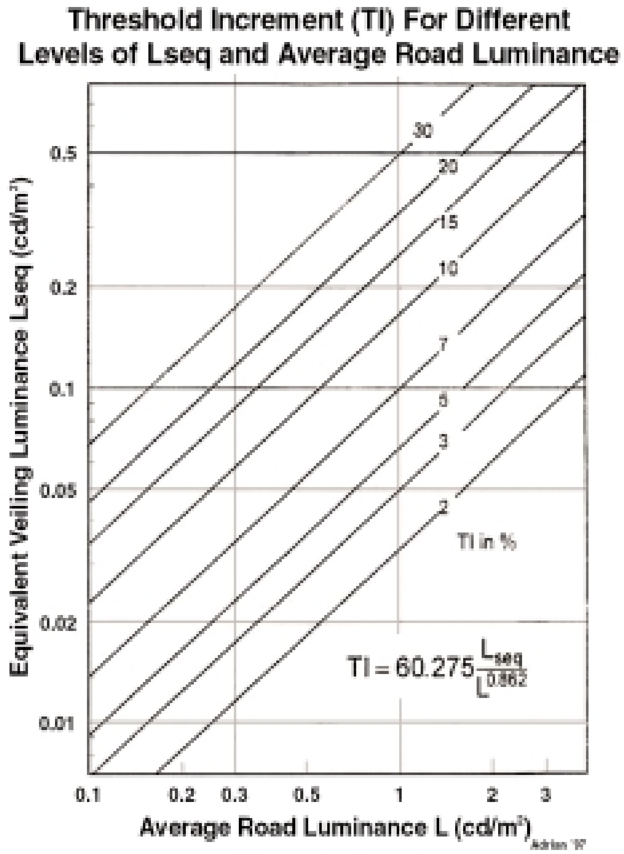

Figure 1. From W. Adrian, D.A. Schreuder. *The assessment of glare in street-lighting*, Light and Lighting, December 1968.

Cataracts

Disability glare is caused by the diffusion of light as it passes through the cornea, lens, vitreous humor, and retina (Bailey and Sheedy 1986; Winter 1985, Allen 1985). This diffusion is the result of imperfections and debris in the optical system that are collectively known as opacities. Light that scatters when it encounters an opacity prior to reaching the outer receptor segments in the retina causes a veiling effect which reduces target contrast and, therefore, visibility.

A cataract is a lenticular opacity wherein the lens becomes clouded. Cataracts are a widespread problem—over 1.5 million cataract surgeries are performed each year (Daily Apple 1999). Besides reducing the total amount of light reaching the retina, cataracts also scatter any light that does pass through, causing a reduction of contrast that can render objects barely visible. Problems with glare from artificial light sources such as headlamps are often, in fact, an individual’s first indication of a developing cataract. In 1988, Schieber concluded that lenticular changes which occur naturally with age, such as cataract, are the primary source of age-related increases in sensitivity to disability glare. As evidence for this, he cited a striking reduction in glare problems after cataract surgery.

Discomfort Glare

Discomfort glare refers to a bright light that, because of its size and luminance, causes a measurable level of subjective discomfort or annoyance. The most popular scale of discomfort glare was first used by DeBoer et al. (1967). It is a ranking of the discomfort caused by a light on a scale of 1–9, according to the following descriptions:

1. Unbearable
3. Disturbing
5. Just acceptable
7. Satisfactory
9. Just noticeable

Discomfort glare is generally influenced by three major factors.

- Location of glare source relative to the line of sight
- Luminance of the background
- Luminance and size of the glare source leading to illuminance at the eye

Experiments conducted by Schmidt-Clausen and Bindels (1974) led to the following formula for the level of discomfort on the DeBoer scale as a function of the three factors listed above:

$$5) \quad W = 5.0 - 2 \log \frac{E_i}{3.0 \cdot 10^{-3} \left[1 + \sqrt{\frac{L_a}{4.0 \cdot 10^{-2}}} \right] \theta_i^{0.46}}$$

where:

W = glare sensation on a scale of 1 to 9
L_a = adaptation luminance (cd/m^2)
E_i = illumination directed at observer's eyes from the ith source (lux).
θ_i = glare angle of the ith source (minutes of arc)

Research has shown that additional factors are related to discomfort glare, including apparent size of the glare source (or its solid angle subtended at the eye) and the source luminance (Sivak et al. 1990). A common measure of discomfort glare used in research is the "Borderline between Comfort and Discomfort" (BCD)[4]. Sivak found that there was a very small but significant relationship between headlamp area and the DeBoer scale. If all the factors in equation 5 for discomfort glare are held constant, increasing the size of the glare source lowers the discomfort level, because the source luminance drops (for constant illuminance E_i). While the effect of size appears to be small, this reduction in source luminance does reduce the level of discomfort.

Other Factors

In addition to the widely accepted parameters just discussed, which have the most significant and predictable impact on discomfort glare, other factors may play a role. The discomfort glare formula presented above is based on highly controlled laboratory studies. Adrian (1991b) has indicated that this formula and other published formulas for discomfort glare "show the same characteristics and yield comparable results." However, Boyce and Beckstead (1991) noted the mediocre correlation between these formulas and the glare ratings obtained in less well-controlled field situations. Other factors that may be related to discomfort glare ratings will be discussed below.

Immediate Surround Luminance

Hopkinson (1963) introduced the immediate surround luminance as an element in his glare formulation. In their review, Boyce and Beckstead (1991) found that including this quantity markedly improved the accuracy of the glare rating. Most vision research is based on a two-luminance world: The target and the background each have a luminance, with the latter generally having the greatest effect in determining the eye's adaptation. Whether we are predicting glare or visibility, the adaptation luminance La represents the multi-luminance world we drive in.

While incorporating the luminance of the immediate surround may improve glare predictions in static situations, under dynamic field conditions there are practical difficulties with such an approach. In the field, the luminance of both the immediate surround and the target tend to vary rapidly. The luminance of the immediate surround is actually more relevant to determining the con-

[4] *BCD is determined by having a subject adjust the intensity of a glare source until its brightness is between a level that is annoying and a level that is comfortable.*

spicuity of an object as defined by the background luminance. In dynamic situations, it seems impractical to consider more than one surround luminance in the calculation of glare. Despite this limitation, it is important to remember that it is the background luminance in its transient state that best approximates the adaptation luminance in any visual encounter on the road. Fortunately, the eye responds rather quickly under normal roadway lighting levels (Adrian 1991a).

Range Effect

The range effect is a shift in the subjective assessment of discomfort based on the range of intensities of the glare sources being evaluated (Lulla and Bennett 1981). If a subject is exposed to a wider ranger of glare intensities, the level of glare that the subject considers tolerable is increased. Although the work of Lulla and Bennett was based on relatively short exposures in the laboratory, it might have consequences for measurements of discomfort glare during night driving.

Olsen and Sivak (1984) showed that the range effect is also present in real driving scenarios. They found that, except at high glare levels, drivers who were exposed to a range of illuminances from headlights gave mean glare ratings that were one to two scale units above those predicted from the Schmidt-Clausen equation. In other words, glare levels predicted by the equation to be "just acceptable" were rated by drivers to be "satisfactory," and glare levels predicted to be "satisfactory" were rated nearly "just noticeable." These findings suggest that, under certain circumstances, permissible glare may be much higher than the equations would suggest, and that this increase in tolerable glare may even be extended further by raising the extreme levels of glare to which drivers are exposed.

It may be that the more comfortable glare ratings obtained in real driving scenarios versus laboratory situations are an extension of the range effect. This would be true if the range which subjects use in evaluating glare exposures is a range based upon prior experience in driving situations and not just the recent experience established in a single experimental setting. Therefore, even when the actual range of glare levels in a laboratory or field study is restricted, more comfortable judgements may be assigned to any given glare level when driving than in the laboratory.

Sivak et al. (1989) reported a practical demonstration of this effect when comparing European and U.S. driver groups. As will be seen in Chapter 4, European headlighting design stresses the minimization of discomfort glare as a high priority. Students with recent driving experience in Germany reported higher levels of discomfort when exposed to glare than U.S. students. The study tested only a small sample of young drivers from one country, and the results may be attributable to language differences in interpreting the discomfort rating scale. Still, the range effect suggests that our experience with glare may well have an influence on how comfortable or disturbing we perceive glare to be.

Task Difficulty

A laboratory study by Sivak et al. (1991) and a field study by Theeuwes and Alferdinck (1996) provide some support for the hypothesis that discomfort glare ratings are influenced by the difficulty of the task being performed. In the Sivak study, subjects performing a gap-detection task reported that a fixed amount of glare caused more discomfort as gap size decreased, making the gap more difficult to detect. Sivak et al. also noted the potential incongruity in discomfort glare models like that underlying equation 5: Conditions such as fog or a dirty windshield increase veiling luminance and thus disability glare, but according to equation 5 such conditions would reduce discomfort, because the peak intensity of the glare source (E) would be decreased and the illumination in the rest of the retina (L_a) would be increased. Yet these conditions make driving more difficult and might increase discomfort if task difficulty were included in the equation.

[5] *The nine point scale used to measure glare is an ordinal scale which means that the intervals along the scale are not equal. In practice it has however turned out to approximate an interval scale.*

The field study reported by Theeuwes and Alferdinck (1996) included two sections of road with similar levels of background luminance but different road markings and curvature. The discomfort glare ratings were much lower (more annoying) on the winding road with no markings. For the study as a whole (which included nine road sections), the glare ratings were much higher (more comfortable) than would be predicted by equation 5, a finding which is attributed to the lack of difficulty in driving all but the one section of winding road without markings. Although the evidence associating task difficulty with the perception of glare is slight and the effect of reducing task difficulty on discomfort glare is unpredictable, most road improvements that reduce the difficulty of driving would also have safety benefits that offset their cost, so that, overall, such improvements might be worthwhile.

Physiological Effects

Age — Research into the effects of age on discomfort glare appears to be inconclusive. Theeuwes and Alferdinck (1996) found that older drivers were more sensitive to stray light, but ratings of glare discomfort on the nine-point rating scale were not sensitive to age differences. In contrast, Bennett (1977) reported a small but significant negative correlation ($r = -0.36$) between BCD and age. The discrepancy between these studies may be explained by the finding of Theeuwes and Alferdinck that the nine-point rating scale does not correlate well with BCD and that in actual driving situations subjects rate glare as less annoying than predicted by the models developed under laboratory conditions.

Eye Color — The amount of light that enters the eye is determined by pupil size, which is is regulated by the dilation and constriction of the iris. Two bands of muscle fibers in the iris, the dilator and sphincter muscles, cause the opening and closing of the pupil. The iris derives its name from the mythological Greek goddess of the rainbow, an indication that its predominant characteristic is color. Unlike the sclera, the white portion of the eye, which is opaque and blocks most incident light, the pigmented iris is translucent. For this reason, the amount of light that enters the eye is dependent on both the pupil size and iris color. A light-colored iris (blue, for example) transmits more light to the retina than a darker-colored iris, where the epithelium contains the same pigments as the iris. In fact, when eye color is extremely light, as with albinos, tinted or colored contact lenses are sometimes prescribed because glare can become intolerable (NOAH 1999).[6]

Corrective Lenses — Lower light levels, such as those on unlighted roads at night, are associated with a state of night myopia. This phenomenon is a result of movement of the accommodative system toward a resting state, which Leibowitz and Owens (1978) found to peak at 1.52 diopters, or 66 cm. If a driver is already myopic, this would increase his myopia.

Many older drivers, while still able to see distant objects well, suffer from presbyopia (farsightedness of the elderly) and so wear some type of corrective lenses to improve their ability to focus on near objects, such as a car's dashboard. With increasing age, the range of accommodation shrinks due to hardening of the crystalline lens in the eye. As a result, night myopia is less pronounced in presbyopic subjects.

It is often observed that corrective lenses such as glasses and contacts can exacerbate the effects of glare, particularly if the lenses are scratched or dirty. The scientific data, however, are inconclusive. For example, Schieber (1988) found that disability glare can result from damaged contact lenses or from corneal injury due to prolonged contact lens usage (see also Miller and Lazerby 1977). Sivak, Flannagan, Traube and Kojima (1999), however, failed to find a difference in the DeBoer ratings of individuals wearing glasses or contacts and those of individuals without visual corrections. However, the Sivak et al. finding that corrective lenses are not associated with increased discomfort glare does not contradict Schieber's result that damaged lenses may cause disability glare.

[6] *The pigment that shows up in the iris is also present in the inner eye. People exposed to high light levels for generations developed darker eyes to reduce inter-reflection in the eye.*

CHAPTER 3
THE PROBLEM OF HEADLIGHT GLARE

Our awareness of a problem with headlight glare comes primarily from direct observation and from the reports of others. Mortimer (1988) cites his own dissertation, a study of drivers aged 19 to 39 in which 65% of the subjects said they were bothered by glare at night, and another study in which one-third of the subjects said glare was a frequent problem. The *San Francisco Chronicle* (June 28, 1999) reported, “Young and old alike, many drivers on the Bay Area’s busy, twisty roads complain of blinding lights in the windshield and rear-view mirror.” The article quoted an informal survey indicating that drivers are convinced that glare is worse than ever.

While there seems to be no scientific explanation for why glare is becoming a greater problem, contributing factors appear to be the introduction of high intensity discharge lights (HID), the proliferation of sports utility vehicles with headlights mounted higher than passenger vehicles, and the use of illegal aftermarket devices. As reported by the *San Francisco Chronicle*, many complaints about HID could actually be about fake HID, “which usually are installed by drivers seeking to look cool. The fakes cause more glare because they diffuse the beam ... posing a safety risk for everyone on the road.”

This chapter will consider two aspects of the headlight glare problem: first, what subgroups are most affected by glare, and second—and most critically— its consequences. Understanding the consequences of headlight glare is the basis for evaluating the importance of countermeasures.

Subgroups Affected Most by Glare

Based on the factors contributing to glare that were identified in the previous chapter, it can be inferred that three subgroups of individuals are at high risk for nighttime glare: those with light eye color, those whose driving is mostly on high-volume, two-lane roads, and the elderly. Another potential high-risk subgroup is composed of drivers with corrective lenses, but this is only a serious factor if the contacts and lenses have been scratched or damaged. Some drivers who have had vision correction surgery, such as radial keratotomy or LASIK, also complain about glare.

In Chapter 2, a formula for disability glare was presented and introduced a factor to account for the effect of age. This formula indicates that, while there is some increase in disability glare among younger drivers, effects begin to increase significantly only after age 40. Results consistent with this model were obtained by Pulling et al. (1980), who conducted simulator experiments that defined threshold glare as brightness from “headlights on oncoming cars so great that potential hazards on the highway could not be distinguished in time...” As discussed in Chapter 2, the increase in disability glare with age is a result of a reduction in the amount and optical clarity of the light transmitted in the eye as the lens and cornea age. These changes increase the relative amount of stray light in the eye and cause this light to scatter more, which increases the veiling luminance and so the effect of glare. Many older people also develop cataracts, which cloud the lens and increase light scattering inside the eye.

There is also evidence that older drivers may be bothered more than younger drivers by discomfort glare. Bennett (1977) reported some experiments which showed that the level of glare that caused discomfort (measured by the "borderline between comfort and discomfort," or BCD) decreased rapidly with age until age 40, after which it continued to decline, although at a slower rate. Schwab et al. (1972) found that drivers, particularly older drivers, were willing to reduce the amount of remuneration they received from a research study in order to avoid having to participate in trials with high levels of glare. After taking family income into account, Schwab concluded that drivers appeared willing to pay about what a polarized lighting system cost at that time. This suggests that, after adjusting for inflation, drivers today would be willing to spend approximately $100 for a device that would reduce headlight glare to acceptable levels.

Consequences of Headlight Glare

Documentation of the consequences of headlight glare is not readily available. It is far easier to speculate about what these consequences might be than to measure them. A controlled field study (Theeuwes and Alferdinck 1996) tested three levels of glare illuminance (namely 0.28, 0.55, and 1.1 lux, or 350, 690, and 1380 cd, at 500 m) and found that even the lowest level of glare resulted in reduced detection distances and, in some situations, greater speed reduction and more steering reversals (thought to be a surrogate measure of fatigue-inducing workload). Surprisingly, the discomfort glare ratings of these glare levels were not related to any of the performance measures.

Very generally, headlight glare has the potential to both increase the frequency of accidents and decrease the mobility of individuals by discouraging them from driving at night. Both of these consequences may be mediated by a reduction in visibility or an increase in fatigue or tension—or by the simple discomfort, and sometimes painful experience, which night driving presents. The following section will discuss the effects of glare on visibility, fatigue, accidents, driver behavior, and mobility.

Effects of Glare on Visibility

The effects of glare on visibility have primarily been studied in the laboratory, in studies that have produced the formulae discussed in the preceding chapter. Of interest here is what, if anything, can be said about the glare-related loss of visibility in field situations. One controlled field study by Cadena and Hemion (1969) demonstrated a reduction in visibility distance that was attributed to the level of headlight glare, although some of the reduction in visibility distance seemed to be due to the distraction of opposing vehicles both with and without headlights. Hare and Hemion (1968) used observations of encounters between opposing vehicles in two-lane, open road situations to develop a formula for the reduction in visibility distance.

Hemion (1969) found that while detection distances decreased in the presence of glare from opposing high-beam headlamps, the distances were actually higher when both vehicles used high beams than when both used low beams, even though both discomfort and disability glare were higher. The additional illumination from the driver's own high-beam headlights increased the target contrast and so compensated for the loss in contrast that led to disability glare. In terms of visibility distance, more is to be gained from using high beams than low beams.

Hemion (1969) found that the position of the glare car relative to the observer had no effect on detection distance over a 1,000-foot range. This observation might indicate that the detection distance was primarily due not to glare but to distraction caused by the presence of an opposing vehicle. On the other hand, the relative position of the glare car may have had no effect because of the competing effects discussed in the previous chapter: Glare increases with higher illumination but decreases with a higher glare angle. As the observer car and the oncoming glare car approach each other, both illumination and glare angle at first increase; then, beyond a certain point, the beam angle of the opposing vehicle becomes large enough that illumination begins rapidly to decrease.

Effect of Glare on Fatigue

One important consequence of headlight glare is its potential ability to cause feelings of stress and fatigue. Schiflett, Cadena, and Hemion (1969) defined fatigue as a state of increased discomfort and decreased efficiency resulting from prolonged exertion on a task. The extent to which a person experiences fatigue is a function of that person's surroundings, including visual conditions. Boyce (1981) pointed out that although the relationship between visual conditions and induced fatigue has been studied for many years, little progress has been made in understanding their relationship. The slow progress could be due to the fact that fatigue is very difficult to define and measure. However, even without experimental evidence, personal experience with driving tells us that fatigue does occur and that lighting conditions, including glare from approaching headlights, may influence its occurrence.

Generally, fatigue is divided into two categories: physical fatigue and mental fatigue. Physical fatigue is well understood; it results from prolonged use of a given set of muscles. Physical fatigue includes physiological changes in the muscles that cause them to simply stop operating; either the muscles become incapable of contracting or the central nervous system stops sending them signals. Mental fatigue, by contrast, is not well understood. Boyce theorized that mental fatigue is nearly impossible to measure directly because it involves the entire body as well as the mind, not just a single muscle or muscle group. Although difficult to define or measure, there is no question that mental fatigue exists, because, as Boyce says, "It is a matter of common experience that prolonged and difficult mental work leads to feelings of tiredness."

Studies that attempt to determine how lighting conditions affect fatigue usually focus on one of the two types of fatigue. Physical fatigue associated with lighting conditions can impair the functions of the muscles of the ocular motor system. Binocular vision, according to Weston (1954), involves at least twelve muscles in every movement of the eye. In addition to these eye muscles, many different facial muscles are brought into play in situations with bright light: Muscles of the lower eyelid, cheeks, and upper lip cause the eyes to squint and give the face a look of grief or distress. Weston concluded that the prolonged use of these "grief" muscles also contributes to the fatigue associated with bright conditions.

Another source of physical fatigue while driving is the effort required to keep the eyes focused directly ahead of the vehicle. Weston described what happens when bright lights, such as passing headlights from opposing cars, pass into the peripheral field. In this situation, the bright light acts as a distraction, causing "visual confusion," and the eyes tend to automatically move toward the light. An effort must be made to keep the driver's gaze directed to the near side of the road instead of toward the blinding light of an approaching car.

Because the onset of fatigue is very difficult to measure, determining relationships between fatigue and variables such as lighting conditions is a challenge. In the study by Schiflett, Cadena, and Hemion (1969), psychological and physiological criteria were used as fatigue indicators. The experiments investigated whether fatigue would cause different driver performance when three different lighting systems were used: a glare-producing high-beam system, no opposing headlights, and polarized headlights.

A two-part study by Schiflett et al. (1969) evaluated the development of driver fatigue in terms of performance on tests given before, during, and after sessions of driving. The tests included psychological and physiological characteristics related to fatigue. In the first part, subjects drove around a runway loop approximately 1.75

miles long while both real and simulated vehicles were used as approaching cars that provided opposing-headlight glare. In the second part, simulated driving in a stationary test complex was used.

In summarizing the Schiflett experiments, Schwab and Hemion (1971) pointed out that although effects were seen in some of the tests, they were not consistent among drivers or even between repeated performances of a single driver, and so the observations could not support or refute the hypothesis that onset of fatigue depended on lighting conditions. The large variance in the data could be explained by the lack of control over what the subjects did during the day before they came to the test site. However, the methodology of measuring psychological and physiological changes in the subjects could still be a successful solution to the problem of scientifically observing the fatigue resulting from glare, and it should be employed in future studies.

Effect of Glare on Accident Frequency

A total of 42,059 deaths occurred on U.S. roadways in 1998. An analysis of the Fatality Analysis Reporting System (FARS) of the National Highway Traffic Safety Administration (NHTSA) showed that, although the number of vehicle miles driven at night represents only about 14% of the total, 45% of deaths took place at night. The severity of the nighttime accident problem is further indicated by the traffic death rate at night, which in 1998 was 4.63 deaths per 100 million vehicle miles, 4.4 times higher than the rate during the day (National Safety Council 1999). This reflects a notable increase from the 1993 rate of 3.9 per 100 million vehicle miles, or 3.2 times higher than the daytime rate.

Nighttime death rates have consistently been the highest in rural driving environments. Of the 18,874 nighttime traffic fatalities in 1998, over 56% took place on rural roads (FARS database). The hazardous nature of rural nighttime driving becomes even more apparent when one considers that only 40% of all vehicle mileage occurs on rural roads (NTS 1999), and less than 15% of that is during the nighttime hours (National Safety Council 1999). For the past decade, the rural nighttime death rate has consistently been about three times the rural daytime rate and about two-and-one-half times the urban nighttime rate (National Safety Council 1988, 1990, 1994, FARS Database, NTS 1999). According to 1988 Pennsylvania Department of Transportation (PennDOT) data, rural accidents are more likely to involve fatalities, whereas urban accidents are more likely to involve property damage. The PennDOT database also showed that the two most common subgroups for nighttime accidents are rural unlighted and urban lighted areas.

Driving safety on rural roads is compromised by a number of factors, including heavy use, frequent curves and intersections, and decreased sight distance, all of which combine with high rates of speed to produce very dangerous driving conditions. NCHRP Report 66 (1979) indicates that glare from oncoming headlights is most often encountered on two-lane rural highways. Glare is also worse on roadways that curve to the left because opposing headlights are directed into the driver's eyes in proportion to the degree of curvature.

Despite the known deleterious effects of glare on the visual system, we seldom hear of a traffic accident caused by glare, and glare is seldom considered a major factor in accident causation. Hemion (1969) found very few states in which "accident reporting forms and procedures made specific reference to headlight glare as a causative factor in vehicle accidents." Seven states out of the 25 contacted by Hemion could readily provide relevant statistics; these states reported that only between 0.5% and 4.0% of all night accidents were attributable to headlight glare. Hemion believed glare data to be under-reported because reporting typically focuses on direct causes and would tend to not consider a vehicle that is no longer at the scene. A later report by Mortimer (1988) also stated that glare is rarely reported as a factor in accidents.

The situation does not appear to be much different today. The FARS database could potentially be used to identify glare-related accidents (NHTSA 1987). The categories in FARS closest to glare effects are codes 23 and 61 under "Person Related Factors: "Failure to Dim Lights or Have Lights on When Required," and "Reflected Glare, Bright Sunlight, Headlights," respectively. However, for accidents coded as 23, it is not possible to tell if the accident was related to lights being on high beam or not being on at all. There were very few accidents coded as 61—only four in 1997, and of these only one occurred at night. The PennDOT accident records system includes a contributing factor labeled "Glare Condition," but the records give no indication as to whether the glare is from opposing headlamps, from the sun, or any other light source. The poor categorization of glare-related accidents could be a result of the State departments of transportation not recognizing glare as a major contributing factor in accidents, or it could be related to drivers' inability to identify glare as a contributing factor. There could be a real yet underreported effect from glare on accidents that has not yet been recognized because accident victims and those who fill out accident forms don't know whether they should report it or how to do so.

There is a real need to improve accident-reporting systems to account for glare as a contributing factor in accidents. Cost-benefit analyses cannot be performed to justify an expenditure of resources on safety improvements without some estimate of the accident-reduction potential. For example, the report by Pulling et al. (1980) mentions the absence of necessary accident data that might support the cost of glare screens, which otherwise appeared to be a productive countermeasure on some types of roads.

Owens and Sivak (1996) analyzed data from FARS for the period 1980–1990 that suggest that visibility and alcohol may play different roles in fatal traffic accidents. Poor visibility appears to be the major factor in situations that have inconspicuous hazards such as pedestrians and cyclists. However, when the weather is clear and inconspicious hazards are absent, ambient illumination does not seem to have a role in fatal accidents; instead, alcohol is the dominant factor. Owens and Sivak suggest that this difference in roles may be due to the effectiveness of marker lights, reflective materials on vehicles, and delineation. Still, problems with the accident reporting system raise doubts about these results. The system makes it far easier to report the involvement of a pedestrian or cyclist than to report the poor visibility of an object that was not even identified. Accidents involving alcohol may sometimes be avoided with improved visibility, but again the accident reporting system does not make the relevant information available.

Nonetheless, on dark roads where disability glare may precede discomfort, drivers are unlikely to be aware of the effect of glare on their vision. Analytically, one must accept the syllogism that since driving is primarily a visual task and glare has a deleterious effect on vision, glare must have a deleterious effect on driving. It should not be assumed that the deleterious effects are necessarily catastrophic. Drivers may compensate for the loss of vison by driving more slowly or otherwise more cautiously.

Effect of Glare on Driving Behavior

There has been very little research on the effects of glare on driving behavior. A study by Theeuwes and Alferdinck (1996) suggests that glare from oncoming headlights has a minimal effect on speed and steering. The study concluded that De Boer discomfort ratings have no predictive value with regard to how much drivers will adjust their speed. Drivers in the study did reduce speed in the presence of glare (by approximately 2 km/h), but not in relation to the amount of glare. The study's analysis of steering wheel reversals and gas pedal reversals showed no relationship to the presence of or the amount of glare.

Effect of Glare on Mobility

Since mobility is a primary goal of the transportation system, anything that degrades mobility is a cause for concern. There is some evidence that problems with glare during nighttime driving have a negative impact on some motorists' willingness to drive at night. Chu (1994), reviewing evidence from the National Transportation Survey, concluded that elderly drivers are less likely to drive at night and during peak hours than middle-aged drivers, and are less likely to drive at night than during peak hours.

As part of another, as-yet unpublished study[1], both an urban (Philadelphia) and a suburban focus group were used in 1997 to study the driving experience of older drivers. Focus groups, surveys, and driver logs were used in the study to document the problems of older drivers with nighttime driving. When nighttime driving was discussed with a group of instructors for the 55 Alive course, problems with glare from oncoming headlights were reported to be the greatest nighttime concern for older drivers. The majority of focus group members listed glare from oncoming headlights as one of their major concerns about nighttime driving, and the suburban group said that reducing headlight glare is one of the factors that would help the most with driving at night.

An open-ended question in the driver biographical logs asked, "What is your greatest difficulty or biggest concern about driving at night?" One third of the total driver-log study group wrote "headlight glare" or "lights from oncoming traffic" as their primary or secondary answer. Forty percent of the urban subjects cited these factors as their greatest concern and 27% of the suburban subjects gave them as their most frequent response. Only four different concerns were cited by urban drivers, whereas suburban drivers cited 11 concerns or difficulties. For both groups, the most frequently cited difficulty regarding nighttime driving was headlight glare.

For this group of older drivers, 29% reported headlight glare to be their greatest concern and almost 21% said that poorly lit roads caused them the most concern. Another 24% of drivers responded with several other difficulties that could be related to roadway lighting: difficulty seeing, bright lights, vehicle breakdowns, and seeing pedestrians or bicyclists. Overall, 74% of the respondents indicated that nighttime driving comfort was related to some aspect of roadway lighting.

Summary

The extent to which glare is a problem for night driving is not easily quantified. In the absence of official statistics or scientific data, evidence of a glare problem is based almost entirely upon subjective reports, most of which are anecdotal. Without data from well-designed experiments, we can only qualitatively assess the deleterious effects of glare, and the economic and safety consequences are left unknown. While there is little doubt that the number of drivers complaining about glare is increasing, the age of the driving population is also increasing. Without good data there is no way of knowing whether the drivers having problems with glare are those with the most exposure to glare situations (such as high-volume two-lane roads), or whether they are older drivers that have visual problems even in the absence of glare. If drivers have basic problems with night vision, solving their problems with glare may increase their risk by giving them a false sense of security and encouraging them to drive more at night.

[1]*Research conducted by The Last Resource Inc. for The Federal Highway Administration under Contract DTFH61-96-C-00023.*

CHAPTER 4
A COMPREHENSIVE REVIEW OF GLARE COUNTERMEASURES

The search for and evaluation of countermeasures for headlight glare has been a subject of discussion from the beginning of automotive lighting. The first attempt at creating a countermeasure was the development and regulation of the headlamp beam pattern itself. Were it not for the need to control glare, the intensity of light from headlamps could be made as great as technologically possible. In fact, the intensity of headlamps is restricted as the result of compromises that determine the headlamp beam pattern. The design of the beam pattern is itself a countermeasure, which is discussed later in this chapter.

The light output from a headlamp, as measured by its intensity in candelas, is not uniform in all directions. The primary goal of headlamp design is to provide sufficient light to see objects on the road while at the same time limiting the amount of glare. The variance in the directional light output of headlamps is illustrated by the headlamp beam pattern shown in Figure 3 in Chapter 5. Although all U.S. headlamps must conform to Federal Motor Vehicle Safety Standard 108 (FMVSS 108), this standard only regulates light intensity at a finite number of test points. As a result, different lamps made for different vehicles by different manufacturers will have dramatically different beam patterns.

Another reason for the variability in beam patterns encountered on the highway is that headlamps are often misaimed, which shifts the beam pattern either horizontally or vertically. In addition if the headlamp height is raised without correcting the aim of the headlamp with respect to the horizontal, the beam pattern will be marginally affected. Both aiming and reduction in lamp height are potential countermeasures discussed in Chapter 5.

The horizontal and vertical curvature of the road changes the relative location of the beam pattern with regard to distant objects. While the beam pattern remains the same with respect to the fixed axes of the vehicle as it traverses a curved road, the location of targets changes, including both the eyes of oncoming drivers and signs or objects on the road. Therefore, the intensity of light directed at these targets and the amount of illumination falling on them also varies. The introduction of dynamic or “smart” headlights (see Chapter 5) is a countermeasure intended to nullify this effect.

Finally, variation in the operating voltage of the vehicle will affect the output intensity of the headlamps in all directions. Although the beam pattern will remain the same, the overall intensity will be either increased or decreased.

Other methods of controlling glare have been documented by Pulling et al. (1980), who discussed five countermeasures for headlight glare: polarizing headlights, glare screens, road delineation, highway lighting, and driving restriction. A more recent report by Duncan (1996) considered the application of a number of state-of-the-art technologies for glare suppression, including polarization, “smart” headlights, modulated headlights, ultraviolet systems, and infrared systems.

Chapters 5—8 discusses these and other potential countermeasures that have been promoted to reduce or eliminate the negative effects of headlight glare. In general, the causes of both discomfort and disability glare produced by headlighting are either opposing vehicle headlights or indirect light sources such as rear-view and side-view mirrors and other highly specular surfaces on leading vehicles or within one's own vehicle. Before considering the countermeasures themselves, it is useful to consider the highway situations that contribute to heightening the effects of glare from vehicle headlamps.

Causes of Headlight Glare

While the fundamental factors that determine disability and discomfort glare were discussed in Chapter 2, to better understand the basis of drivers' glare problems one must consider how these factors are affected by geometric and vehicle parameters. While it is not possible to attribute causality to any one factor, it is useful to identify the roadway and vehicle conditions that contribute to glare and to gather evidence to try to isolate the most serious offenders.

Illuminance from the glare source is determined by the photometric intensity distribution of the oncoming headlamps, the aiming and height of these lamps, whether high beam or low beam is used, and the distance of the glare source from the observer. The greater the intensity directed toward an observer, the greater the illuminance reaching the observer's eyes. Headlamp intensity is controlled by the headlamp design and the beam pattern, discussed elsewhere in this chapter. In general, headlamps are designed and aimed to produce greater intensity below the horizontal and to the right of the vehicle center line. While the Federal Government's published standard FMVSS 108 is intended to control glare by limiting the amount of light above the horizontal axis, roughly half of all vehicles on the road are driven with improperly aimed headlamps (Copenhaver and Jones 1992). The reasons for this are numerous and are discussed below, under aiming as a countermeasure for glare.

The closer the observer is to oncoming headlights, the greater the illuminance and, therefore, the greater the glare. The inverse-square law describes the amount of light reaching an observer; it simply states that illumination from a point light source is inversely proportional to the square of the distance from the source. Figure 2, below, shows the illumination resulting from two light sources of different intensity levels as a function

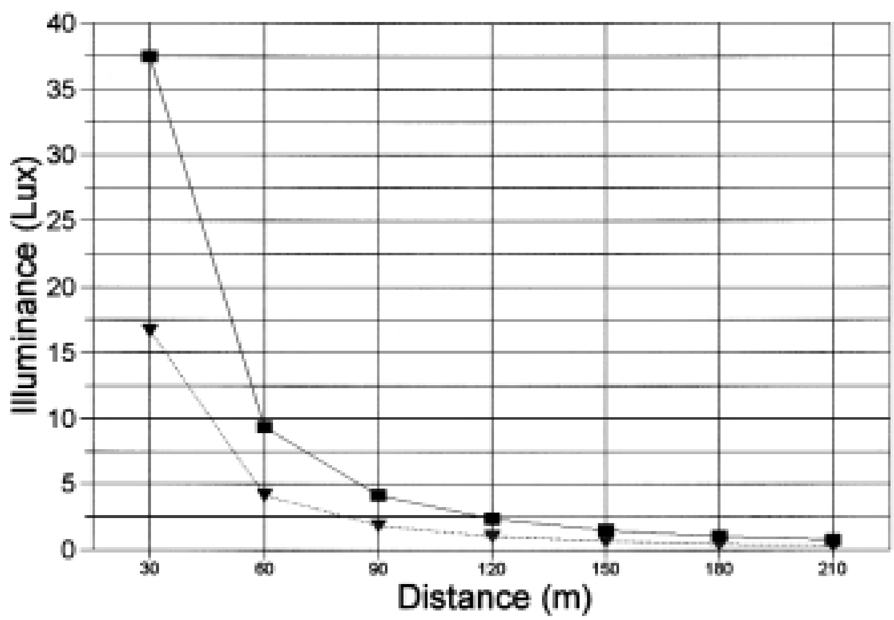

Figure 2. Illumination at increasing distance from two light sources.

of distance from the source. There are two phenomena to observe: 1) At near distances, illumination increases rapidly as the light source is approached; and 2) illumination falls off rapidly with increasing distance—if the distance is increased by 50%, the intensity must more than double[1] to obtain the same level of illumination. In other words, while glare increases dramatically as a light source is approached, there is an equally dramatic reduction of illumination as distance is increased.

While illumination increases with proximity to an oncoming vehicle, in practice the level of glare is often reduced. This happens because the glare angle increases as the glare source gets closer and, if the observer continues to look in a given direction, this increase in glare angle offsets the effects of increasing illuminance. The dynamic relationship between distance and veiling luminance is discussed in Chapter 5.

High-intensity discharge (HID) headlights are a recent advance in lighting technology with numerous advantages for both auto manufacturers and consumers. Auto manufacturers like HID headlights because of the reduced requirements for power, greater control of the beam pattern, and greater flexibility in stylistic parameters. Consumers who have them like them for their stylistic properties and because they offer dramatic improvements in visibility. Consumers who don't have them are divided between those who want them for stylistic reasons and those who hate them because they are perceived as responsible for glare.

The importance of style is shown by the popularity of aftermarket conversion kits, which offer the style without the improvements in visibility. Several companies offer halogen bulbs that are coated blue to look like HID bulbs. These bulbs are not legal and produce less light than a normal halogen bulb. While they may be annoying, they are not contributing to the glare problem. Other conversion kits that use true HID bulbs (usually xenon lights) are available, but they are limited in practice to systems that use single-filament bulbs (separate bulbs for low and high beams). These conversions cost upward of $1,000 and are not guaranteed to have the photometric performance required by government safety standards. Although both the cheap blue halogens and the expensive HID conversions are illegal in the United States, they are nevertheless being purchased and installed. While there does not appear to be any data about the prevelance of these units on U.S. roads, their popularity is evidence of the importance of style to the consumer.

HID headlamps typically have two to three times the light flux (volume) of halogen lights, but because the HID filament is smaller, they allow the light to be controlled more precisely. This causes a sharper cutoff, which results in both higher intensity on many beam angles below the cutoff and in flashing, which is produced when roadway undulations cause the cutoff to sweep quickly up and down across oncoming driver's eyes or the mirrors of preceding vehicles. As a result the design gradients for HID lamps tend to be closer to the test points. Because of the larger filament size of halogen sources, a lamp designer must use more gradual transitions or risk having a greater proportion of units fail photometric testing. Properly aimed, and when not flashing, these HID lamps may not appear significantly brighter than halogen sources if their size is relatively the same. However, if misaimed, and when flashing, these lamps will appear brighter and will produce significantly more glare than a normal halogen lamp.

Another problem magnified by the greater intensity of HID is dirt accumulation on its lens. Dirt acts as a diffuser on any headlamp and can result in additional stray light being directed above the horizontal axis into the eyes of oncoming drivers. When the total light flux is tripled, as it is with HID, this diffusion becomes a much greater problem. While headlight aim has always been a concern, HID may force the introduction of countermeasures to respond to the misaim problem.

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[1] *Intensity must increase by a factor of 2.25 to maintain the same illumination when distance is increased by 50 percent under the inverse square law:* ($E_1 d_1^2 = E_2 d_2^2$).

Whether one encounters legal factory units or illegal after market conversions, improperly aimed HID systems are going to exacerbate any problem that might exist with glare. Even if properly aimed, the sharp cutoff and the flashing this produces, may require further control of the beam pattern. (See the discussion of the photometric distribution in Chapter 5.)

The glare angle from oncoming headlights is the angle between the direction of a driver's gaze and the direction of the glare source. Glare angle depends on the distance between the opposing vehicle and the observer vehicle, the road geometry, and the offset of the opposing vehicle paths, which is determined by the number of lanes in one direction, the lane of occupancy, and the median or shoulder widths. Overall, the glare angle is smallest when the opposing vehicle is furthest away so the illumination is low. Fortunately, when the opposing vehicle approaches and illumination increases significantly, the glare angle becomes sufficiently large to minimize the effect of glare. Two-lane roads and freeways without medians or left shoulders provide environments where the glare problem is exacerbated by small glare angles at close distances, where there are high levels of illumination. While the glare angle is increased during encounters on right-hand curves, glare is actually worse on left-hand curves because approaching drivers are exposed to the brighter parts of the beam pattern.

Dynamic relationships between beam pattern and distance to an opposing vehicle were evaluated for several lateral separations by Powers & Solomon (1965). This report showed that, for a typical two-lane road approach, the level of glare increases gradually as the oncoming car approaches from a separation of 2,000 feet until it reaches 300 to 400 feet; as the car comes closer than this, the glare level drops sharply. At first, the glare is caused by the portion of the beam pattern that is near the peak intensity point; although relatively bright, the source is far away. As the vehicles approach each other, the distance declines, but the driver is seeing less candlepower (further to the left of center on the headlamp beam distribution). The eventual dropoff in glare is so sharp both because of the large increase in glare angle and because at short distances the light comes from parts of the beam pattern where the output is very low. With increased lateral separation, the overall veiling luminance decreases and the peak will occur at somewhat greater distances. At large distances, veiling illuminance is greater on left-hand curves and less on right-hand curves because of the portion of the beam pattern to which approaching drivers are exposed. This is discussed further below, under wide medians as a countermeasure.

Background luminance is generally determined by the reflectance of background (usually the pavement) and the illuminance on the pavement (usually from headlights at near distances and ambient light or fixed roadway lighting at far distances). When driving, a driver may look at objects on or off the road. Some objects, such as overhead signs, may be seen with the sky as a background, while objects on the side of the road, such as signs, may be seen with buildings or foliage as a background. Most objects have the pavement as a background, so the luminance of the pavement is thought to have the greatest effect on driver eye adaptation. In general, concrete pavements are more reflective and therefore have higher luminance than asphalt; however, the reflectivity of pavements is affected by wear and other factors. Pavement luminance contributes to the glare problem primarily when illumination is low, as is the case on dark rural roads. The glare problem is apparently not as severe on brighter urban roads because the driver's adaptation level is higher. This observation is the motivation for the use of fixed lighting as a countermeasure for glare. However, fixed lighting will produce its own glare, which must then be controlled.

Size of the glare source is determined by the physical dimensions of the glare source and the distance between the driver and the glare source. At close distances, headlamps are no longer point light sources; increasing their size while holding their light output constant will reduce discomfort. On the other hand, as an observer approaches a reflective surface, the relative size of the surface increases but, as a result of the inverse-square law, the light intensity and the discomfort glare also increase. This apparent disparity in the effect of source size on glare is due to the fact that when headlamp size is increased, luminance is reduced, whereas the luminance of a reflective surface generally remains constant when its size is increased under constant illumination. Headlamp size is generally not a significant factor in glare since there is not much variability in headlamp size with current designs. However, as we shall see in Chapter 8, the development of larger-sized headlamps is a potential countermeasure to discomfort glare, despite the current trend towards smaller headlamps.

Glare source luminance is determined by both the intensity and the area of the headlamp: Luminance is increased when either intensity is increased or area is decreased. As mentioned earlier, the intensity of the lamp is modulated by the beam pattern and luminance will vary depending on the angle from which it is viewed. As long as headlamp size is not varied, there does not appear to be any problem with headlamp luminance that is not related to headlamp intensity, beam pattern, or aiming.

Driver age affects the experience of glare on the road in the same way it does in the laboratory. Age, as we saw in Chapter 2, has a significant effect on the magnitude of disability glare: Older drivers encounter higher levels of disability glare than younger drivers under the same lighting conditions, and anecdotal reports indicate that older drivers complain more about glare and are more restricted in mobility at night. However, there is some inconsistency in the literature concerning whether older drivers are more discomforted by glare than younger drivers.

Reflective surfaces outside the vehicle can be a problem. For example, reflective surfaces on a leading vehicle stopped at a traffic light can be very discomforting. Interior surfaces of vehicles can also become illuminated and cause some glare, but under current Motor Vehicle Safety Standards, adopted in 1966, vehicle surfaces are required to have glare-reducing matte finishes (this is why the old chrome windshield wipers have disappeared). This countermeasure is already well implemented and so will not be discussed further. A removable object in the vehicle can also be a glare source, but the driver always has the option of moving such an item.

If the glare source is a reflective surface, both the illuminance and luminance from the source are dependent on the reflectance of the surface as well as on the photometric properties of the light illuminating the surface. If the reflecting surface is inside the observer's vehicle, the illuminating source is usually the following vehicle. If the reflecting surface is on a lead vehicle, the illuminating source may be the observer's own headlights.

Glare from a reflecting surface on a leading vehicle depends on the distance of the observer from the glare source. As the headway between the vehicles increases, illumination from the leading vehicle is reduced and the size of the glare source projected on the retina of the eye becomes smaller. The problem is at its worst when two vehicles are stopped in traffic. Since both vehicles are stopped, the glare can usually be controlled by looking in another direction.

Glare from mirrors is the result of the reflection of headlamps; its magnitude is based on the optical distance to the image of the headlamps. Since mirrors simply redirect the optical path, it is the distance between the headlamp and mirror plus the distance between the mirror and the driver's eye that determine the illuminance at the driver's eye. The transmission of the rear window and the reflection characteristics of the mirror (about 4% for a typical day/night interior mirror on its night setting, 50% for exterior mirrors) must be considered.

Olson and Sivak (1984) observed two distinct differences between glare from mirrors and glare from oncoming headlamps: First, there is typically more than one mirror, which increases the glare problem; and second, the following vehicle may remain in a relatively fixed position for a long period of time, which raises questions about the time-related effects of glare.

The principles governing glare from mirrors are similar to those for oncoming headlights: distance, beam pattern, intensity, and aiming all affect the amount of glare. The part of the headlight beam pattern of a trailing vehicle that is directed at the mirrors of a leading vehicle will change as the headway changes and depends on the mounting height of the trailing vehicle's headlamps. The glare angle, which ranges from 35 to 55 degrees in passenger cars (Olson and Sivak 1984), is determined by the location of the fixed mirrors and not by the location of the following vehicle. In general, any countermeasure that can decrease the headlamp intensity, increase the headway, or reduce the height of following vehicles will reduce the illuminance from the glare source and so also reduce the amount of mirror glare.

Types of Countermeasures

Chapters 5 through 8 describe various countermeasures that have either been implemented or proposed for controlling the effects of glare from vehicle headlights. Some of these countermeasures are intuitive and have been deployed to some extent for many years. Others rely on state-of-the-art technology to achieve results that are not at all obvious. Table 1 lists a wide variety of potential countermeasures, characterized by the primary source of implementation, whether it be the driver, industry, or a government agency.

While there are many methods for reducing the amount of glare attributable to headlights, only a few countermeasures may be implemented unilaterally by the driver. Many countermeasures must either be implemented by a highway agency (usually the state department of transportation, or DOT) or by automobile manufacturers, with or without the Federal mandates that make specific types of equipment available or legitimize changes in vehicle or headlamp design. In Europe, headlight glare is limited by aiming the beam downward, whereas in the U.S., the beam is aimed upward. Both approaches recognize the tradeoff between glare and visibility; the European standard accepts reduced visibility while the U. S. standard accepts more glare. The implementation of these philosophies is discussed in Chapter 5.

Countermeasures in Table 1 are grouped according to their principal method of attaining a reduction in glare: reducing intensity, reducing illumination, increasing the

Table 1. Countermeasures grouped by method of implementation

Chapter 5. Reduce the intensity or luminance of the glare source	
Industry	Photometric Distribution
Driver	Aiming
Industry	Adaptive Headlamps
Industry	Color Corrected Headlamps
Industry	Headlamp Height
Chapter 6. Reduce the illumination that reaches the driver's eye	
Government/Industry	Polarized Lighting
Driver	Night Driving Glasses
Government	Glare Screens
Industry/Driver	Anti-Glare Mirrors
Chapter 7. Increase the glare angle	
Government	Wide Medians
Government	Independent Alignment
Chapter 8. Methods that indirectly may result in glare reduction	
Industry	Ultraviolet Headlights
Government	Fixed Roadway Lighting
Government	Restricted Night Driving
Government/Driver	Corrective Lenses and Ophthalmic Surgery
Industry	Headlamp Area

glare angle, or through an indirect effect. A brief description of these four categories is presented below. Some countermeasures may fit in more than one category; we have placed each in the category that seems most appropriate. Table 1 shows the countermeasures to be discussed in each category and whether the driver, industry, or a government agency should take the lead in implementation.

Reduction of intensity or luminance. Some countermeasures reduce glare by reducing the luminance of the glare source or the intensity of light aimed in a driver's direction. Modification of the low-beam pattern and independent alignment of opposing directions of road are examples of this type of countermeasure.

Reduce illumination at driver's eye. Another group of countermeasures is intended to block or filter light, thereby reducing the amount of illumination reaching a driver's eye. Anti-glare mirrors, glare screens and some types of night-driving glasses (those marketed as glare reducers and not for optical corrections) are prominent examples.

Increase the glare angle. Some countermeasures reduce glare by increasing the angle between the glare source and the road ahead. Wide medians are the most common method of implementing this strategy.

Indirect benefits. The last group of countermeasures do not themselves directly reduce glare, but have the potential to indirectly reduce glare by either reducing the illumination needed for vision or raising the adaptation level of drivers. Ultraviolet lighting and fixed roadway lighting are prominent examples of these countermeasures.

CHAPTER 5

COUNTERMEASURES THAT REDUCE THE INTENSITY OF GLARE SOURCE

(Control of the Lower Beam Pattern)

- **Photometric Distribution**
- **Aiming**
- **Adaptive Headlamps**
- **Color Corrected Headlamps**
- **Headlamp Height**

Photometric Distribution

Every driver is aware that some headlights are brighter than others. This variation in brightness is the result of variation in the beam pattern, aiming, and height of the headlamps. The beam pattern in the U.S. is governed by Federal Motor Vehicle Safety Standard 108 (FMVSS 108), which specifies minimum and maximum values of luminous intensity at approximately 20 test points given by the angles in degrees from the horizontal and vertical axis of the lamp. The minimum values are intended to insure the ability of drivers to see critical targets such as lane lines, signs, and pedestrians, whereas the maximum values are the countermeasure to control glare. Originally, FMVSS 108 had maximum limits but no minimum requirement for light output above the horizontal; recently, the standard was modified to require some minimum levels above horizontal so as to maintain the visibility of retroreflective overhead signs.

The light output from a headlamp, as measured by its intensity in candelas, is not uniform in all directions; rather, it varies according to a photometric distribution that is documented in a headlamp beam pattern. A beam pattern representing the median value of 26 sealed-beam and replaceable-bulb lamps conforming to U. S. standards is shown in Figure 3. In this example, the headlight intensity is represented by the shading at all points specified by the angle from the horizontal and vertical axes. The upper band in green represents intensities less than 400 cd; the next band represents intensities between 400 and 800 cd; and each successive band closer to the center represents a further doubling of intensity, to 1600 cd, 3200 cd,

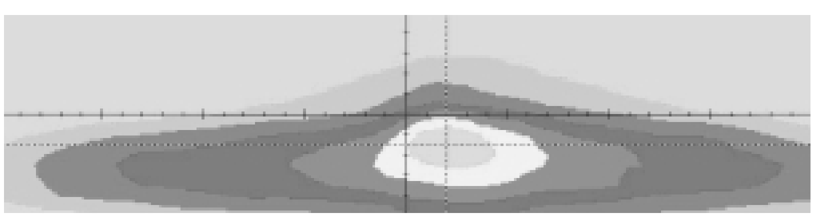

Figure 3. US headlamp beam pattern mapped from -20 to +20 degrees horizontal and -5 to + 5 degrees vertical.

and so on. The inner circle represents a light intensity greater than 12,800 cd.

The headlamp beam patterns encountered on the highway vary considerably as a result of several factors. First, headlamp regulations such as FMVSS 108 specify minimum or maximum output only at a small number of test points. Light output can always be greater than the minimum or less than the maximum at these test points and can take any value at all other locations. Lighting technologies to date have resulted in beam patterns that vary gradually throughout the beam pattern, without major reversals in intensity, which effectively spreads the control of a few test points over a much larger area and minimizes variability to some extent. Still, lamps made for different vehicles by different manufacturers will have dramatically different beam patterns.

The potential of using modifications in the beam pattern as a countermeasure to control glare is most evident when the U.S. and European headlamps are compared. European countries have chosen to set the beam pattern to protect oncoming and leading vehicles from glare, to permit visual aiming, and to provide wider and brighter foreground illumination than is found in the U.S. Compared with U.S. headlamps, the European lamp has a “low cutoff” without a peak, which limits the amount of light emitted above the horizontal axis. The absence of a peak in the beam pattern makes the lamp easier to aim visually. A negative consequence of sharp cutoff is the occurrence of flashing, which occurs when the vehicle traverses roadway undulations and the cutoff sweeps quickly across oncoming drivers’ eyes and mirrors in preceding cars.

A beam pattern representing the median value of 33 halogen lamps conforming to European standards is shown in Figure 4. The sharp cutoff of the European headlamp is apparent from the horizontal contour lines, which rise from left to right until the cutoff position is reached. By contrast, in the U.S. headlamp the contour lines peak just to the right of zero on the horizontal axis and gradually decline to the right of the peak. By moving the peak to the right, European headlamps direct more light above the horizontal axis toward objects on the right side of the road and less light to the left, limiting the exposure of oncoming drivers to glare. The U.S. beam pattern directs considerably more light above the horizontal axis than the European pattern, resulting in better visibility of overhead signs and other objects on vertical curves. Such improved visibility has been realized even without minimum requirements, which until recently did not exist, to ensure that some light be directed above the horizontal axis.

In addition to fundamental differences between the U.S. and European beam patterns, there is a very significant difference between the way headlamps are aimed in Europe and in the U.S. Headlamps in the U.S. are aimed so the beam pattern in the real world is aligned identically to the pattern measured in the laboratory. In Europe, headlamps are aimed downward between 1.0% and 2.0% when installed, depending on headlamp height. After installation a 3% downward aim is acceptable. The European beam pattern and downward aim result in less glare, but also in shorter seeing distances and much less sign illumination. Another undesirable consequence is the flashing mentioned previously.

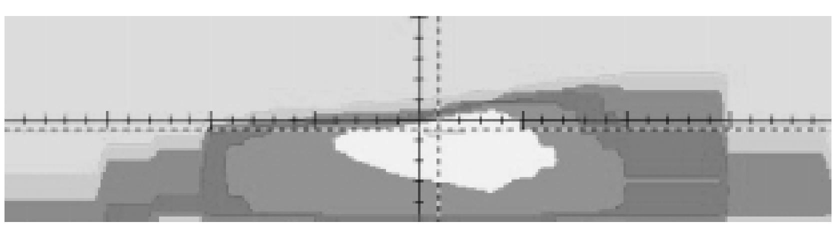

Figure 4. European beam pattern mapped from -20 to +20 degrees horizontal and -5 to + 5 degrees vertical.

The U.S. has resisted adopting the European beam pattern and aiming practice because it severely limits visibility distance. Limiting the effective illumination range of low beams to 200 ft or less is not acceptable on U.S. roads, where low beams are used for urban and suburban driving at relatively high speeds. In Europe, low beams are used strictly for city and heavily urban low-speed driving. To accommodate the European practice in the United States, all overhead signs would have to be illuminated and roadside signs would have to be placed lower than the 7-ft standard on U.S. rural roads. Signs mounted nearer to the road surface are not only more difficult to see because of blockage by other vehicles and by snowbanks in northen climates, but also are more susceptible to the accumulation of dirt by splashing from vehicles moving past them, which further reduces their visibility.

In the United States, users of illegal European (ECE) headlamps sometimes aim the cutoff at the horizon, following the U.S. practice, which gives much better seeing distance but more flashing glare. Users seem to think that the ECE beam is superior, but this is only true if it is misaimed. The recent amendment to FMVSS 108 to provide an option for visual/optical (VOA) headlamp aiming has resulted in headlamps with a sharper cutoff for visual aiming purposes, but in their pursuit of a headlamp harmonized with the ECE beam pattern, vehicle manufacturers sometimes demand a cutoff that is sharper than necessary for the United States. Such a sharp cutoff, with the high aiming necessary to meet the requirements of FMVSS 108, make flashing more likely to occur in the United States. Setting a limit on the cutoff sharpness could help reduce this adverse glare problem.

It is also likely that attempts to develop headlamps that meet both U.S. and European requirements will reduce the amount of light available above the horizontal axis. Headlamps that would once have come close to the maximum values allowed by FMVSS 108 will, if harmonized with ECE requirements, produce light much closer to the minimum values allowed by FMVSS 108. While this may reduce some of the problems drivers encounter with headlight glare, it will also reduce the visibility of traffic signs.

Comparing the U.S. and European low beam, Sivak et al. (1992) point out that each approach is advantageous in certain traffic conditions, but neither appears to be superior overall. They suggest that this lack of a generally superior alternative appears to have created a positive attitude toward international harmonization. Use of adaptive, or "smart," headlamps is another approach to resolving this disparity, because such lamps seek to maintain visibility while controlling glare.

Research on the Low Beam Photometric Pattern

There have been numerous attempts to improve low beam headlighting patterns, but, while these attempts have advanced understanding of the problem, a comprehensive solution has not been attained. The goal has been to develop a beam pattern that provides adequate visibility, such as of pedestrians, signs, lane lines, and obstacles, while at the same time minimizing glare for oncoming traffic and into rear mirrors. These efforts have included computer modeling, research, and policy efforts, a few of which are briefly described here.

In the 1970s, the Ford Motor Company supported the development of computer based visibility models that could be used to evaluate alternative lighting systems. In the 1980s, NHTSA became interested in developing a vehicle performance standard for headlighting that would improve safety while giving manufacturers more freedom in lighting design. These efforts contributed significantly to knowledge of roadway lighting, but did not result in any consensus for changes in FMVSS 108 due to disagreements over assumptions and methodological problems. Faced with difficulties in analytically evaluating headlamp performance and in defining a new performance standard, NHTSA turned its efforts to improving the aim of the beam patterns that presently exist. As a result, a revision was made to FMVSS 108 in 1997 that allowed for an optional set of test points to improve objectivity and accuracy in the aiming of VOA headlamps. Currently, research is being conducted at the University of Michigan to develop a subjective rating of the photometric distribution of the forward illumination of different vehicles for different types of driving.

Headlamp comparisons with visibility models — Beginning in the 1970s, researchers at the Ford Motor Company (Bhise et al. 1977) developed a computer model named CHESS (Comprehensive Headlamp Environment Systems Simulation) to evaluate the performance of low-beam headlighting patterns. The model computes a weighted sum of several performance measures—including the fraction of pedestrians and delineation lines detected with and without an opposing glare car, and the fraction of drivers that were discomforted by glare—and so obtains a figure of merit (FOM) for each headlamp evaluated. The components of the FOM that the model computes are also useful performance measures by themselves. Basic inputs to the model for a headlamp evaluation include the headlamp beam pattern, height, and aiming; environmental variables, and driver vision variables.

The FOM reflects the fraction of the total distance traveled on a simulated test route in which the visual environment can be considered adequate, where "adequate" is defined as being able to see both pedestrian and delineation targets at safe distances without unacceptable levels of glare. The simulated route included roads representative of the various road types and topography in the U.S. Calculations for the FOM are based on encounters with opposing vehicles and pedestrians on a mixture of different road types.

The FOM is highly dependent on several somewhat arbitrary assumptions, including where pedestrians are placed within the road geometry and the importance, or weight, given to discomfort glare. In addition, the results of the model are dependent on the way the performance criteria are defined. However, the more basic problem is a basic consequence of the inverse square law: Because illumination decreases with the square of the distance from the source, very large increases in candlepower are required to create a useful increase in illumination. Comparisons in the study of prototype headlamps showed that there was only a 10% difference in performance between designs, whereas variation in environmental conditions produced a performance change of 60%. The authors pointed out that there were "no means of relating the Figure of Merit to safety and certainly no basis for assuming that a given change in the Figure of Merit will produce a proportional change in accidents."

The Ford Motor Company studies concluded that the U.S. low-beam pattern is close to the optimum. Several alternate beam patterns were evaluated, including a mid-beam design proposed by NHTSA that attempted to improve visibility without increasing glare by concentrating the beam intensity in the right lane. The problem with this design was that light was directed where intended only if the beams were properly aligned and the car was on a straight road. While the mid-beam pattern produced some improvement in performance, it might be difficult to control the beam pattern to the tolerances necessary to produce the desired result. Internal research by NHTSA with the CHESS model showed that while some alternate beam patterns resulted in a modest improvement in performance, improved performance could also be obtained by changes in mounting height and by improved aiming.

In the mid 1980s, NHTSA became less interested in headlamp comparisons and more interested in the development of a headlamp standard related to driver needs, particularly with regard to safety. The important question was not what low-beam pattern was best, but rather how to specify a low-beam pattern that met driver requirements for visibility and the control of glare, given that the specification would follow the current method of specifying minimum and maximum beam intensity at a limited number of points (with some variation to allow for the necessary manufacturing tolerances).

Vehicle-based performance standard — One of NHTSA's primary goals has been to establish a set of vehicle specifications that could replace existing specifications that apply only to headlamps. In 1985, as part of its comprehensive review of FMVSS 108, NHTSA published a Notice of Request for Comment asking for suggestions on how to make the standard more performance-oriented and less design-restrictive. The goal was to reduce the burden on the regulated parties while simultaneously reducing the burden on NHTSA of responding to design-related requests for changes in requirements. Prior to this notice there had been an increasing volume of petitions from vehicle and headlighting manufacturers developing new headlighting systems. Another motivation for the review was concern that, because there were then no minimum requirements for headlamp light intensity above the horizontal, headlamps being introduced—mostly by European manufacturers—might not provide sufficient illumination for adequate visibility of signs.

In general, the comments received were in favor of requirements that were more performance-oriented, and the process gave rise to a long-term NHTSA effort to develop a vehicle-based roadway illumination performance requirement. There was also hope that a performance-based specification could lead to harmonization between U.S. and European (ECE) specifications. However, there was almost universal agreement that any new performance requirement should not involve testing of the vehicle as a whole, only the headlighting devices.

One early NHTSA approach to developing a vehicle-based specification was to simply convert the existing lamp specifications to a corresponding set of vehicle specifications. This approach was not adopted for the low beam for several reasons: First, there was no basis for relating the specification to satisfaction of safety requirements; second, it did not address the concern about limited light above the horizontal; and finally, it did not provide a basis for continuing international discussions on harmonization of headlight specifications.

The vehicle-based approach which was eventually adopted consisted of identifying a set of driving conditions where roadway illumination is needed on the basis of safety and then determining the necessary amount of light to provide visibility for safe driving in these situations. The driving situations that were identified included the following safety elements: avoidance of pedestrians and other on-the-road objects, staying within lane boundaries, control of oncoming (direct) and following (mirror) vehicle glare, and highway sign illumination. The driving situations were chosen and prioritized based on careful analysis of fatal and non-fatal day and night accident data in which accidents were characterized as pedestrian, off-road, roadside, and overturn. According to the unpublished data used in the analysis, which considered both the number of accidents and the accident rate per million vehicle miles, pedestrian accidents seemed to be of most concern on urban arterials and off-road accidents seemed to be of most concern in rural areas. This approach had the advantage that it could provide a basis for developing any of several vehicle-based specifications, including those related to the existing requirements and compatible with the performance of existing lamps, or those that provide an improvement in safety by using vehicle lighting systems.

To help in establishing the vehicle-based performance standard, computer models were developed that were based on the original Ford visibility models. These models determined the amount of light needed to see pedestrians, signs and lane lines at distances required for safety, with and without a glare car present. Both direct glare and mirror glare were considered in the models. More than a thousand individual illumination requirements were identified and then condensed into between 20 and 30 test points, which then became the basis for a proposed rulemaking issued in May, 1989. Some of the test points were minimum requirements to provide for visibility of signs (including overhead signs), pedestrians and lane lines; others were maximum values to control glare. Unlike FMVSS 108, which specifies the light intensity at specific angles from the beam direction, the proposed rulemaking specified the minimum and maximum illumination at target points defined in terms of both angle and distance. Specification of the illumination at a distance instead of the intensity along a beam angle was necessary because of the variations in headlamp placement, particularly mounting height. A computer program was needed to determine whether a particular headlamp's photometric pattern could meet the requirements when the headlamps were mounted at the height and spacing appropriate to a particular vehicle.

Proposals for a vehicle-based performance standard were rejected for a variety of reasons, including disagreements over the assumptions made in the modeling, methodological errors, and the overall conceptual complexity of a vehicle lighting system. Headlamp height, itself a motivation for development of the new standard because of the serious problems with mirror glare, increased the complexity of the vehicle standard and so contributed to its demise. Numerous controversial assumptions had to be made for such factors as pedestrians' location, activity, and clothing; sign retroreflectivity; drivers' age and visual abilities; and roadway geometries. Methodological problems included determining weighting factors that reflected priorities among the conflicting needs for visibility and control of glare and establishing the amount of glare to which drivers were subjected.

Effects of Increasing the Intensity of the Low Beam Pattern — Flannagan et al. (1996) conducted an empirical study of the distance at which pedestrians could be seen, in which headlamp intensity was increased while the light intensity from an opposing glare vehicle was also increased proportionately. The study found that increasing the intensity of light from both vehicles by a factor of 3.8 increased the visibility distance by 17%. This result is consistent with previous research (Hemion 1969a, Johansson et al. 1963), which found that visibility improved when high beams opposed high beams compared to situations when low beams opposed low beams.

These results suggest that, if visibility distance is the sole criterion, there may not be any upper limit to how intense low-beam headlamps should be. However, such a conclusion is not completely warranted, because differences in beam patterns, aiming, and road geometry mean that the conditions found in controlled field experiments, where the illumination of two opposing vehicles could be increased by equal amounts, are unlikely to occur in practice. Further as Flannagan pointed out, "there may be a level at which people simply will not tolerate the subjectively discomforting effects of glare, or at which glare indirectly affects objective performance through its effects on subjective comfort." Flannagan added that research is needed to understand the consequences of discomfort glare, "including possible effects of discomfort glare on objective behavior." Theeuwes & Alferdinck (1996) found that subjects were less willing to look at a light source when illumination was higher. Discomfort glare may affect performance by increasing fatigue or by causing drivers to look away from the road so that some objects on the road could only be seen with peripheral vision.

Need for Sign Illumination — Lighting may be made more efficient by improving sign legibility, using larger, more readable letters and the most retroreflective sheeting available. Russell et al. (1999) concluded that with signs placed on straight and level roads and made of high-performance Type III sheeting, "better than 99% of the 1,500 vehicles observed would provide sufficient illumination for right-shoulder mounted signs and more than 90% of these vehicles would provide sufficient light for the left-shoulder mounted signs, but only about 50% of them would provide sufficient light toward overhead signs." These figures dropped to 90%, 45%, and 10% for the more-common Type II sheeting, or if the Type III sheeting had been degraded for a few years. Sign legibility would be still less for older drivers; Russell defined "sufficient illumination" only in reference to younger drivers.

Given the desire in the U.S. for harmonization with the European beam pattern, it is unlikely that there will be any future increase in the amount of light directed at signs. If the beam pattern were to be altered to provide less light above the horizontal axis, overhead signs would have to be externally lighted or replaced with repeated signs on both sides of the road. Both solutions are costly, and, because of limited sight distance, roadside signs are not as effective as those mounted overhead.

With the states continuing in their quest to eliminate self-illuminated signs because of their energy and maintenance costs, it appears that the current preference of government is to continue to rely on illumination from low beams for the visibility of reflective signs. Some relief from sign illumination requirements is offered by new types of retroreflective sheeting, such as the proposed ASTM type IX, which is more efficient at the wide entrance angles created by sign placement overhead or at extreme offsets. Improvement in retroreflective materials should certainly be seen as a countermeasure to glare. Whether these materials provide sufficient retroreflection for visibility with the illumination provided by today's vehicles is open to question, but surely the use of these materials would limit the need for headlamps to generate more illumination and thus more glare.

Rating System for Consumer Education — Currently, NHTSA is taking a very different approach from that of the past. Instead of trying to pick the best headlight system or to develop a vehicle standard that would enable all headlight systems to satisfy driver performance requirements, the focus is now on developing a rating system that would empower consumers to pick the headlight system that best meets their needs and type of driving.

A study (UMTRI 1999) was initiated in 1999 by the University of Michigan Transportation Research Institute to assess the feasibility of vehicle headlamp ratings of new cars that would provide buyers with information analogous to what they might learn from a nighttime test drive. For example, NHTSA might rate headlamps as part of the New Car Assessment Program (NCAP), which gives new vehicles one to five stars on the basis of crash tests. Headlamp performance might similarly be rated from one to five stars and the information posted on the NHTSA web site. The benefits of a headlamp rating system might include helping individual consumers to make choices that better serve their needs and helping to bring about a general improvement in the quality of headlighting by increasing public awareness of differences in headlamp quality.

Advantages to Altering the Low-Beam Photometric Distribution

Altering the low-beam photometric pattern can reduce glare for on-coming drivers, improve the visibility of pedestrians, roadside objects, and left-mounted and overhead signs, and make it easier to visually aim the headlamps. Achieving all three goals is generally not possible, so priorities must be set and tradeoffs made.

Reduced glare. Reducing light above the horizontal axis, for example by using the European beam pattern, can significantly reduce drivers' exposure to glare.

Improved visibility. Requiring a minimum amount of light above the horizontal axis and to the left can improve the visibility of pedestrians as well as of signs located to the left or overhead. This requirement has been implemented to some extent by the VOA beam pattern.

Visual aiming. Manipulating the beam pattern to have a recognizable horizontal cutoff makes it easier to visually aim the headlamps and to ensure that proper aiming is maintained. This can improve visibility as well as limit exposure to glare.

Disadvantages to Altering the Lower Beam Photometric Distribution

The disadvantages of altering the low-beam photometric pattern are opposite the advantages:

Increased glare. Attempts to provide light in certain locations for left-mounted and overhead signs can increase the level of glare, particularly when vehicles meet each other on horizontal curves.

Reduced visibility. The most significant disadvantage to lowering the photometric beam pattern or moving it more toward the right edge of the road is generally reduced sight distance and reduced visibility of left-mounted and overhead guide signs.

Poor visual aiming. Attempts to create a peak in the beam pattern to improve the visibility of certain objects, such as overhead signs, reduce the accuracy of visual aiming and result in poor illumination of the desired targets on horizontal curves.

Summary

"In Everyman's conception of safe and comfortable night driving, the headlamps of his vehicle illuminate the roadway far ahead, and the headlamps of other vehicles never decrease his vision by glaring into his eyes, either through the windshield or from the rear-view mirrors" (Haney and Mortimer 1974). Attempts to reach a compromise by allowing some light above the horizontal axis, but not enough to cause a severe glare problem, have proved very difficult. As mentioned above, it is generally accepted that sight distances as low as those in Europe are not suitable on U.S. roads. Exactly what distance is necessary has never been agreed on because it depends on vehicle speed, what needs to be seen, and the threat potential of the visual information.

The four visual targets generally considered most important include road delineation (including edge lines, pavement, and delineators), pedestrians, signs, and objects on the road. Studies of accident data have not been able to rank-order these targets. Many believe that road delineation, which when deficient can contribute to run-off-the-road accidents, is the most important, while others think that the focus should be on pedestrians. Without a clear, unequivocal ranking of what needs to be seen based upon expected accident reduction, the appropriate tradeoffs between seeing distance and glare can not be made. In designing roadway lighting, the Illumination Engineering Society has used a surrogate vertical surface 7 inches square, with 18% reflectivity, to represent an object in the road.

Neither changing the current U.S. beam pattern nor increasing its overall intensity appears to offer any meaningful advantage to drivers. In addition, because illumination decreases with the square of the distance from the source, very large increases in candlepower are required in order to create a useful increase in illumination. This has led to the conclusion that it is not practical to provide adequate illumination of pedestrians at speeds greater than 35 or 45 mph.

Without a means of relating headlamp performance to safety, there is no basis for assuming that headlamp changes would produce a proportional change in accidents. Instead of solving problems by changing the amount or the distribution of light, existing light could be used more efficiently by improved maintenance and design of signs (including such aspects as retroreflection and angularity), better delineation and other traffic control devices, and by the use of countermeasures discussed later in this report. Another approach is to reduce the need for visibility distance by placing further limits on speed for night driving. Fisher (1970) has suggested that a maximum speed of 50 mph should be considered for night driving. Certainly, differential day/night speed limits are consistent with the recognized importance of visibility to safety and the reduced visibility that naturally occurs after dark.

Headlight Aim

In order to achieve the beam pattern intended by the lamp designer, headlamps must be properly aimed. Misaiming headlamps will result in reduced visibility and/or increased glare for other drivers. Proper aim and a clean lens, not the beam pattern, are the most significant aspects of headlamp performance. While FMVSS 108 specifies limits for headlamp intensity at several test points above the horizontal, misaim and road curvature alter the actual location of the projected beam pattern. As a car ages, headlamp alignment changes because of road vibration; however, rear loading of the vehicle, once thought to have a significant effect on aiming, appears not to be an important factor (Copenhaver and Jones 1992).

The effects of misaim could be minor or dramatic, depending on the amount of misaim. Misaiming shifts the beam pattern horizontally or vertically; it should be apparent from Figures 3 and 4 that the effects of horizontal misaim are not as great as those of vertical misaim. Sivak et al. (1993) found that horizontal misaim of 1.5 degrees in either direction had no practical significance with U.S., European, or Japanese lamps. However, vertical misaim of 1.5 degrees had practical significance for U.S. lamps and even 1 degree miscuing resulted in significant effects for U.S. and practically as significant effects for European lamps. Measurements of misaim are made using mechanical aimers that determine horizontal and vertical error from an ideal target at 25 ft; the error can be expressed in either inches or degrees. The SAE lighting inspection code rejects headlamps with more than a 4-inch vertical or horizontal error—this is slightly less than one degree.

Before 1983, all headlamps had sealed beams and were equipped with aiming pads in a standardized location, making them all capable of being mechanically aimed. Mechanical aimers measure the level of the headlamps relative to the floor slope and to each other. Following the adoption of replaceable-bulb lamps in 1983, manufacturers developed on-board mechanical aiming devices to solve some of the problems of aiming with external mechanical devices.

In the 1990s, NHTSA began to consider altering the low-beam photometric pattern to make it more sharply defined. It was felt that the revised pattern would facilitate visual aiming of headlamps and might become the basis for a global beam pattern. Visual aiming was seen as desirable partially because of General Motors data that showed that most facilities, both private and state operated, check and adjust headlamp aim visually rather than with the more precise mechanical aimers. This observation was supported by studies of headlamp aiming showing that only roughly one out of every two vehicles have both headlamps aimed properly (Olson 1985, Copenhaver and Jones 1992). As stated in the Federal Register (1995), "In the most common form, aim in state inspections is judged subjectively by the eye of an inspector viewing a headlamp beam pattern cast upon a distant vertical surface, such as a wall or screen." Automatic leveling devices are available as optional equipment on more-expensive vehicles, and are often standard equipment, along with headlamp washers, on vehicles equipped with HID lamps.

In March, 1997, an amendment to FMVSS 108 provided both a laboratory specification for visually/optically aimable headlamps before installation and a field specification for headlamp aim after installation (Federal Register 1997). The VOA laboratory specification included tables of minimum and maximum intensity values similar to those used for mechanical aiming of sealed-beam and replaceable-bulb lamps. The field specification intended for visual aiming provides for a cutoff or sharp transition between regions of high and low luminous intensity. Horizontal aim must either be fixed or the headlamp must have a built-in vehicle aiming device, because a cutoff for visually adjusting horizontal aim does not exist—specifications for features in the beam that can result in accurate visual horizontal aiming have not been identified.

Research on Aiming

Copenhaver and Jones (1992) conducted a study of the headlamp aim of 768 vehicles, half from a periodic motor vehicle inspection (PMVI) state and half from a non-PMVI state. Both headlamps were aimed correctly in slightly more than half the vehicles from the PMVI state and in slightly less than half of the vehicles from the non-PMVI state. Vertical misaim was more common than horizontal misaim, but both were a significant problem. Usually, vertical misaim moved the beam pattern upward and horizontal misaim moved it toward the left. Trucks and vans appeared to be more susceptible to misaim than cars. Variability was very large, with 10% of the vehicles misaimed more than what the equipment could record—a 10-inch error at 25 ft.

The study identified many factors that were not related to misaim, including the type of headlamp, its height above the ground, vehicle load, and design of the headlamp. There was no significant relationship between the number of months since headlamp inspection and headlamp aim, suggesting that shortening the inspection interval may not reduce misaim.

One of the more interesting findings concerned vehicle age. Although the average amount of misaim did not vary significantly as a function of year of vehicle manufacture, the fraction of vehicles with misaimed headlights was significantly higher for older vehicles. For example, both headlamps were correctly aimed in 68.9% of 1991 vehicles but in only 35.8% of 1986 vehicles. In other words, older vehicles were more likely to have their headlamps aimed outside the acceptable SAE tolerance, although the amount of misaim for any one year was no different from any other. This artifact of the study could be due to the extremely high variance within each set of data, or it could be because 10% of the misaim values were labeled "out of range," limiting the misaim values in a way that created a bias toward improving the score of older vehicles.

The practical effects of misaim on glare from rear-view mirrors were reported by Miller et al. (1974), who found that reflected glare from the misaimed headlights of following vehicles exceeded the just-tolerable glare from oncoming headlights. With vehicle separations as short as 50 ft, properly aimed low-beam headlights produce less mirror glare than direct glare from oncoming high-beam headlights at 600 ft. When misaimed, however, the low beam can produce more glare with intercar spacings as close as 150 ft than this oncoming high-beam level. The study found a greater increase in glare from low beams than from high beams when headlamps were misaimed upward. Low beam headlamps misaimed upward only one degree increase the illumination in the rearview mirror by a factor of three to four with the following vehicle in the same lane, and a factor of eight or more when the following vehicle is in the passing lane. With vehicle separations up to 400 feet (following vehicle in the same lane), these misaimed headlamps produce more glare than oncoming high beam headlamps at 600 feet, while vehicle separations of 150 feet or less would result in more glare than from oncoming high beam headlamps at 1200 feet. When the following vehicle is in the passing lane, separations less than 400 feet will produce more glare from headlamps misaimed upward only one degree than oncoming high beam headlamps at 1200 feet. To counteract the negative effects of a low-beam misaim of only one degree, mirror reflectivity would have to be reduced to 10%.

Advantages and Disadvantages of Aiming as a Countermeasure

There is no question that incorrectly aimed headlamps contribute to glare, and therefore proper aiming is a real and effective glare countermeasure. Re-aiming headlamps annually during vehicle inspections is a low-cost procedure that would help correct some problems that contribute to glare. It remains to be seen what effect the availability of visually aimable headlamps will have on headlamp aim in aging vehicles. There are no data to suggest how frequently aiming should be checked, so only the more expensive automatic aiming systems can be said to ensure a lasting improvement.

Summary

Because misaim magnifies all other problems with the low-beam photometric pattern, misaim is clearly the place to begin finding effective countermeasures for glare. Such measures as changing the low-beam pattern or the headlamp height will not be effective if headlamps continue to be misaimed. Research is needed to see whether the availability of visually aimable headlamps has improved the aim of vehicles in the fleet, or whether states should raise the headlamp aiming standards in their inspection procedures.

Since public complaints seem to be mostly about glare from newer vehicles, headlamp aim in vehicles with HID lamps seems to be a logical place to apply corrective solutions.

Adaptive Headlighting

Failure to perfect the lower beam pattern has primarily resulted from inability to meet the dynamic requirements of the road and environment, although variability in the height and spacing of headlamps and the difficulty in keeping them properly aimed are contributing factors. Adaptive forward illumination refers to a tuning of the low-beam photometric pattern to meet the dynamic requirements of changing weather and geometric conditions. It is based on the assumption that no static beam pattern is optimal for all driving situations. While the same assumption was the basis for allowing manual switching between high and low beams, drivers do not use high beams efficiently, if at all. Adaptive headlighting seeks to satisfy lighting requirements that change with speed, road condition, topography, traffic conditions, and so on, by modifying the beam pattern automatically.

Most development of these systems has occurred in Europe. Mannessero et al. (1999) described several functions that adaptive headlighting might perform, including bending (for improved illumination of a curved lane), high-speed freeway (increased visibility distance and control of glare), and other modified beam patterns to meet the special requirements of town driving, country driving, adverse weather, and driving at dawn and dusk. Proposed systems either combine several lamps, each adding special-purpose beam patterns to a basic pattern, or use optical-mechanical parts that provide special lighting functions. Hogrefe and Neumann (1997) described the research and control functions associated with adaptive light pattern (ALP) systems that use a combination of lamps. Kobayashi et al. (1997) reported the construction and field evaluation of a system that used optical-mechanical parts together with high-beam, low-beam, cornering-beam, and fog lamps.

Honda Motor Corporation has developed an active headlight system that redirects the beam in response to the action of the steering wheel. Another Japanese initiative uses activation of the turn signal to change the direction of the beam pattern. Other development efforts are reviewed by Wörner (1999) and Rosenhahn (1999), and Duncan (1996) cites a system that uses an array of headlamps that are selectively activated to alter the beam pattern.

Research with Adaptive Headlighting

Manassero et al. (1999) reported the road-test results of a system used to help develop the best photometric patterns for different lighting functions. Adaptive systems are in the very early stages of development and additional research is needed both to improve performance and to develop control strategies for determining when and how the lighting system is switched from one function to another. Such research will undoubtedly lead to the integration of additional sensors that can provide the needed data input.

Sivak et al. (1994) reported on three studies of an active headlight (AH) system developed by Honda and Stanley Electric. One study evaluated the effects of the system on pedestrian visibility, another on the effect on discomfort glare, and a third on obtaining a subjective rating of the system with respect to several parameters. In the first study, the AH system increased visibility of the pedestrian by 14% on left curves and by 2% on right curves. Oncoming traffic was not included, so these results exclude the effects of disability glare. The second study found an increase in discomfort glare with the AH system on left curves, but an improvement on right curves, where the mean DeBoer rating was better than 5 (acceptable). In the third study, the subjective ratings were not very conclusive, with approximately half of the subjects preferring the AH system and the other half preferring normal headlighting. Whether or not they liked the system, most subjects commented on the wider field of view it provided. Many of the problems identified in the studies could be addressed in a future redesign of the system; however, many of the subjects were bothered by the movement of the headlights, a drawback that might be difficult to overcome.

Advantages

Adaptive headlighting offers the potential to provide visibility beyond what is now available with the low-beam photometric pattern, and to do so without any increase in discomfort glare. The limitations of static systems, which cannot illuminate the same sections of the road on both straight and curved sections of highway, can be overcome.

Disadvantages

Regulations. Depending on the particular scheme proposed, adaptive headlighting might require new regulations to permit nonconforming beam patterns and variations in aiming, as well as to define the switching strategies that determine when each is invoked.

Human Factors Effects. The negative reaction of drivers to moving headlights has been noted. More significant problems may occur as drivers learn that the adaptive headlighting system may prevent them from seeing objects on a curve that they had been looking at along a straight road.

Tradeoffs Needed in Design Parameters. Efforts to choose the "best" beam pattern or define a vehicle standard based on the driver's need for illumination failed, in part, because of disagreement about what drivers need to see and where they must see it and the priorities for resolving conflicts. The AH system does not escape these controversies; the system's design and control strategies must answer the same questions. The same assumptions that defeated efforts to develop software for the best beam pattern and attempts to develop a vehicle standard are now being made about the design and construction of AH systems.

The skepticism of the preceding paragraph was also voiced by Duncan (1996), who suggested that it may be difficult to dynamically reduce glare for oncoming drivers. A dynamic system would have to sense oncoming headlights and reduce illumination accordingly, but if both cars had adaptive systems each would extinguish light directed in the other's direction until the illumination dropped below the sensor's threshold. This could result in an on/off oscillation around the threshold level, which could both be psychologically disturbing and produce a negative impact on vision.

Summary

Adaptive headlighting is in its infancy, and it is far too early to assess its effectiveness as a countermeasure to glare. One might ask the obvious question that, if we have not been able to maintain proper aiming of a fairly simple mechanical device such as the replaceable-bulb headlamp, what new problems will occur with a more complex system that relies on multiple sensors and a computer? There is little doubt that such systems can be designed to improve visibility, but their effect on glare will not be known until they are subjected to research and evaluation. Still, there is a lot of interest in these systems, and one or more may be marketed soon. Whether they will be a countermeasure to or a contributor to glare is not known at this time.

Color-Corrected Motor Vehicle Headlights

An innovative proposal (Karpen 1998, Karpen 2001) that might improve visibility and reduce eyestrain is to add color correction to sealed-beam, halogen, and HID headlamps. Like the proposal for rear-view mirrors to be discussed in Chapter 7, the headlamp proposal (Karpen 1996) would incorporate at least 5% by weight of neodymium oxide doping into the glass used for the headlamps—including any glass with reflective surfaces—so as to reduce the amount of yellow light emitted by the headlights. To reduce the presence of yellow light in the spectrum of HID headlamps, neodymiunm oxide doping would be added to the inner arc tube of the high-intensity lamp in concentrations up to about 3.0% by weight, or to the outer glass lens in concentrations between 5.0% and 30% by weight (Karpen 1999).

The neodymium oxide doping allows production of a concentrated light beam with a unique spectral energy distribution, which, according to Karpen, promotes night vision and visual acuity in darkness by emphasizing the contrast-producing red and green light portions of the visible-light spectrum. The greatest absorption of yellow light-by the doped glass occurs for wavelengths between 568 to 590 nanometers (Karpen 1996).

In addition to the visibility benefits, Karpen claims that reducing the emission of yellow light lessens eyestrain and the reduces the visual discomfort caused by the headlights of oncoming vehicles at night. With the yellow part of the spectrum removed, total light output of the headlamp can be increased without increasing eyestrain. The increased amount of light results in better contrast and improved nighttime visual acuity.

The characteristic absorption of a neodymium oxide glass (also called Neophane glass) affects color vision in a unique way. Red and green hues are strongly accentuated, and colors containing red stand out especially clearly. Karpen suggests that, under light from Neophane glass headlamps, a red stop sign would appear redder and motorists would find it easier to see road signs at great distance against a background of green vegetation.

Research on Spectral Content of Light

Effects on Visibility. Research on the effects of lamp color can be divided into studies of visibility and studies of discomfort. Karpen (1996) cites a number of research papers related to neodymium lamps. Bouma (1938) describes color shifts under the influence of Neophane glass, including a shift of orange and yellow toward red that was experienced as an increased “warmth” of the yellow. Green, which under incandescent light became a somewhat dubious yellow-green, was restored to green under Neophane glass. White and very unsaturated colors were shifted in the direction of blue-violet. Karpen believed that Bouma’s results show that Neophane glass has the advantage of preserving most colors, albeit in a more saturated form, and of making orange-yellow warmer.

A physiological explanation of how the eye sees color and the theory behind the hypothesized effectiveness of the proposed headlamp design is beyond the scope of this paper. Some explanation is provided by Karpen, on the basis of a paper by Gouras and Zrenner (1981). However, a key concept for the discussion of color correction technology is the distinction between photopic and scotopic light. Photopic light has a spectral distribution matching the sensitivity of the bright-light receptors in the eye, the cones. The peak sensitivity of the cones is for green light with a wavelength of 555 nanometers. The spectrum of scotopic light matches the sensitivity of the dim-light receptors in the eye, the rods; rod sensitivity is peaked in the blue-green, at a wavelength of 507 nanometers. Light meters are conventionally designed to measure light of different wavelengths in proportion to photopic sensitivity, so the measured luminance corresponds most closely to the brightness that the eye would perceive at relatively high ambient light levels.

There has been some research into color-corrected fixed roadway lighting. Janoff (1996) compared the effect on visibility of high-pressure sodium, metal halide, and a scotopically rich metal halide lamp, all at 250 watts power in a cobrahead luminaire with a glass refractor. While the high-pressure sodium lamp was more efficient producing the most lumens per watt, the metal halide lamp and the scotopically rich metal halide lamp provided a higher level of visibility per lumen.

Several studies at interior lighting levels (Berman et al. 1993; Berman et al. 1994, Berman et al. 1996) have shown that visual acuity and contrast sensitivity are determined by pupil size, and that pupil size and brightness perception are effected by rod activity. Collectively, these studies suggest that with lamps rich in scotopic spectral content, less luminance (as measured with a photopic meter) is needed for visual performance than with conventional lamps, which have a higher yellow content. This idea was supported by Adrian (1997), who stated, “As the spectral sensitivity of the eye is shifting to the blue with lower light levels, blue and blue-rich power distribution of the light appear brighter and achieve higher levels of visual performance.”

Janoff (1999) reviewed several research papers (including Janoff and Havard 1997, Rea 1990, and Lewis 1997) that evaluated the effects of lamp color in roadway and outdoor lighting on visual performance. The review concluded that the effect of spectral content depends on the level of ambient illumination and the nature of the visual task. Spectral content is not important for foveal tasks, which involve objects located straight ahead, where vision is sharpest, and that are in the mesopic range (adaptation approximately .034 to 3.4 cd/m2, which includes the range of night driving). However, off-axis tasks at mesopic levels can be affected by a lamp’s spectral content. Research by Lewis (1998) that was summarized by Janoff indicates that driver reaction times are shorter at adaptation levels of 1 cd/m2 and below with scotopically rich metal halide lamps than with non-scotopically rich lamps such as high-pressure sodium Other studies (Boyce et al. 1998, Mehra 1998) showed that color-naming performance was better with metal halide lamps than with high-pressure sodium lamps.

Discomfort Glare. While increasing the relative scotopic content of a light source might possibly improve visibility, it may well do so only at the cost of increasing discomfort. Fugate and Fry (1956) investigated the role played in producing discomfort by the constriction of the pupil after brief exposures to light. They found that the amount of pupillary constriction at the borderline between comfort and discomfort varied with the size of the momentary stimulus, greater constriction resulting in greater discomfort. If blue-rich lamps produce a smaller pupil size than other lamps, then discomfort glare might be increased—as has in fact been found by Flannagan, Sivak, and Traube (1994)—even as visual performance is improved. Karpen's claim that yellow light is more discomforting than blue is not easily explained by prior research and should be further investigated.

Sullivan and Flannagan (2001) recently tested color-correction technology by comparing the discomfort glare produced by neodymium, tungsten-halogen (TH), and blue-tinted replacement lamps. The results were consistent with the earlier findings of Flannagan et al. (1994): When all three headlamps were adjusted with neutral density filters to have the same photopic illuminance, TH headlamps produced the least discomfort. This seems to support the notion that yellow light is less discomforting than blue (see discussion of night driving glasses below) and confirms the earlier study by Flannagan, Sivak, and Traube (1994).

Advantages and Disadvantages of Neodymium Headlamps

Neodymium technology, if shown to be effective, should be less costly than almost any other countermeasure for controlling glare. However, the effect of any change in the rendition of color must be tested with regard to the recognition of objects on the road that are critical to safe driving. With respect to headlighting, such objects include yellow warning signs, orange construction signs, and various retroreflective hazard delineators and pavement markings. The Maryland Department of Transportation study, which found that neodymium sunglasses with a notch filter between 580 and 600 nm completely blocked out yellow LED warning signs and traffic signals, demonstrates the need for thorough testing before this technology is accepted. Even if there is some improvement in the visibility of some objects with neodymium headlamps, such a gain will have to be weighed against any loss in visibility of other objects and against any increase in discomfort glare.

Summary

While lamps rich in scotopic spectral content appear to help with some visual tasks under low-level light conditions, the effects on discomfort glare and fatigue are still in question. While Karpen suggests that yellow light is more discomforting and causes more fatigue than light of other wavelengths, most previous research suggests that yellow light is actually less discomforting.

Given the lack of certainty in the research, color-corrected headlamps cannot be recommended as an effective countermeasure for headlight glare at this time. However, variation in the spectral content of lighting is a countermeasure worthy of extended investigation. While the issues under debate by researchers in the field are extremely important, they are beyond the scope of this paper. Clearly, further research is warranted to determine the effect of neodymium (or other scotopically rich) headlamps on visibility and glare in a night highway environment. One thing is certain: If proven effective, neodymium headlamps should be cost-effective, because very little investment would be required to install the devices.

Headlight Height

The FMVSS 108 standard specifies that motorized vehicles should have both headlamps mounted at the same height, one on each side of the vertical centerline, and not less than 22 in (55.9 cm) or more that 54 in (137.2 cm) above the road surface. Sivak et al. (1997) measured 15 of the best-selling cars and 15 of the best-selling light trucks and vans and reported a sales-weighted headlamp height of 24.4 in (.62 m) for cars and 32.7 in (.83 m) for light trucks and vans, including SUVs.

Allen (1985) concluded that “there was no basis in highway safety for allowing headlights to be above the eye level of the driver of a passenger vehicle.... All vehicles ... should be required to have the headlight height and spacing within a few inches of one another so that headlight aim and light-output pattern can minimize headlight glare for everyone.” Mortimer (1988) recommended that FMVSS 108 be amended to “limit the mounting heights of headlamps to within the range of 22 to 30 in. on passenger cars, pickups, vans, trucks, and motor cycles.” Presumably, he would add SUVs to this list today.

Lamp height contributes to glare in the same way that misaim does: Changing the headlamp height shifts the beam pattern. If the headlamp height is raised for a given beam pattern without reaiming the headlamp, a greater intensity will be directed at greater elevations above the road. One consequence is a modest increase in the illumination reaching the eyes of drivers of oncoming vehicles, but the greatest effect is an increase in the illumination reaching the mirrors of leading vehicles at the short inter-vehicle distances of following or passing.

According to the American Association of State Highway and Transportation Officials (AASHTO, 1994), vehicle heights have been decreasing since the 1960s. For design purposes, driver eye height has now been established at 1.07 m (42 in) for cars and 2.4 m (94.5 in) for trucks. The high-mounted headlights on SUVs and pickup trucks create visibility hazards for drivers of cars, and the popularity of SUVs has acted to raise the average vehicle headlamp height. When a full-size SUV follows a smaller sedan at night, the SUV’s high-mounted lights shine almost directly into the side and rear-view mirrors of the leading vehicle. With headlamps going higher and with lower driver eye height in many vehicles, it is not surprising that more people are experiencing discomfort glare when driving at night.

Recognizing that, to control mirror glare, headlamp height should not be above the height of side and rearview mirrors, the SAE task force on headlamp mounting height is considering the ramifications of reducing the maximum mounting height of headlamps on highway vehicles (SAE 1996). Since side-view mirrors are generally lower than the interior rear-view mirror and are often even lower than driver eye height, headlamp heights as low as 36 to 40 in are being considered. However, there is no clear consensus of what the limit should be.

The two concerns delaying any specific recommendations by the task force are the reduction in visibility distance, which is expected to be small, and the effect on the legibility of signs, particularly overhead signs. The concern is not only about the loss in visibility, but also about what actions drivers might take to compensate for this loss. Still, the majority opinion of the task force is that there is no reason to be concerned about a loss of visibility for drivers of SUVs. The report noted that “the marginal detection distance loss for some vehicles is offset by the greater good of reducing glare for the vast majority of passenger vehicle drivers.” Dissenting opinions favored other methods of glare control, including changes in beam distribution, headlamp output, and mirror efficiency.

Research on Headlamp Height

Mortimer (1974) reported the results of a computer simulation of rear-view mirror glare with a vehicle following at 100 ft that used headlamps mounted at various heights. With a 30-inch mounting height, the illumination from rear-view mirrors was about the same (1.72 lux) as that encountered from oncoming high-beam headlights at 600 ft. The rear-view mirror illumination from all properly aimed headlights mounted higher than 30 inches exceeded this tolerance value. With headlamps mounted at 42 inches, mirror illumination from properly aimed low beams exceeded the maximum 3-lux criterion for long durations suggested by Olson and Sivak (1984). This level of glare could be reduced to below the criterion by reducing the interior mirror reflectivity by a factor of 10. The model results assumed that interior mirror reflectivity was 0.85 and exterior reflectivity was 0.55.

Mortimer’s data make it clear that headlamp height is most important if headlamps are misaimed upward. A one-degree upward misaim of a vehicle following at 100 ft increased the illumination received from rear-view mirrors by a factor of about four. At a height of 42 inches, one degree of upward misaim resulted in glare levels as high as 15 lux.

Whether this level of glare can be ameliorated by a decrease in mirror reflection is uncertain without further simulations, but greater amounts of misaim will certainly create more significant glare problems, and these will be exacerbated by higher headlamp mounting heights.

The effect of changes in headlamp height on the visibility of retroreflective signs was studied by Sivak et al. (1993). If headlamp height is reduced while keeping the height of the driver's eye unchanged, the separation between headlamps and eye will increase. Small increases in this "observation angle" may result in reduced visibility distances for retroreflective devices, including signs and road markings, that are more pronounced for large trucks than lighter vehicles. Some trucks may exhibit poor braking performance, and any safety problems with these vehicles might be magnified by reductions in visibility.

Sivak calculated the relative brightness of Type III retroreflective signs mounted on the left shoulder, on the right shoulder, and in the center, as a function of headlamp mounting height. The signs on the shoulders were mounted 4.3 m from the road edge and at a height of 2.1 m, and the center sign was mounted 6.1 m overhead. The study found that at far distances (305 m, or 1000 ft) there was a modest (10%) decrease in detection distance for drivers of large trucks compared with drivers of cars. At near viewing distances (152 m, or 500 ft), if the initial luminance of signs to cars was high, the effect of the increased observation angle on legibility for drivers of heavy trucks was not great, but if luminance was low (6.8 cd/m2), there was a reduction in legibility of 22%. While the study did not single out SUVs, the results for light trucks suggest that the effects of lowering SUV headlamp height will be minimal.

Advantages

Lowering headlamp height to below 40 inches will reduce the glare experienced by the drivers of leading vehicles from their side and rear-view mirrors. The greatest reduction in glare will be achieved if headlamps are aimed properly and low-reflectance, preferably automatic, dimming mirrors are used inside and outside the leading vehicle. While it would be desirable to place a headlamp height restriction on all vehicles, the prevalence of SUVs and small trucks suggest that the greatest advantages would be achieved with this class of vehicles.

Disadvantages

The reduction in glare from lowering headlight height or aiming higher-mounted headlamps downward must be considered in conjunction with the drop in visibility. If headlamps are aimed downward to correct for excessive height, the visibility of distant objects will be reduced. Lower headlight positions are not a problem in passenger cars because in these vehicles the driver's eye height is also low, close to the height of the headlights. For best visibility of retroreflective objects, headlights on heavy trucks need to be high—closer to the height of the driver's eyes—to maintain brightness equivalent to that obtained by cars. The magnitude of the loss in visibility from reduced headlamp height and the consequences for traffic safety have not been well researched. However, the research by Sivak et al. (1993) suggests that the loss may not be great, particularly for SUVs.

Summary

While it would be best if all vehicles could have a similar height and spacing of headlamps (Allen 1985), this might not be practical, because it would suggest that driver eye height should be restricted to a narrow range for both cars and trucks. In any event, fixing headlamp height and spacing is not likely to happen, because the consumer is more interested in style, versatility, and functionality than in glare reduction for other drivers.

Reducing the headlamp height on trucks, SUVs, and other large vehicles to a level below the height of drivers' eyes in cars or car side-view mirrors is a more realistic and desirable goal. Because of their relatively higher speed and lane selection ability, cars generally find it easier to avoid being followed or passed by large trucks than SUVs and light trucks. Given the prevalence of SUVs and light trucks and the greater ability of a driver of a car to avoid prolonged exposure to mirror glare from heavy trucks, it makes sense to target SUVs and light trucks for implementation of this countermeasure.

CHAPTER 6
COUNTERMEASURES THAT REDUCE ILLUMINATION REACHING THE DRIVER'S EYE

- **Polarized Lighting**
- **Night Driving Glasses**
- **Glare Screens**
- **Anti-glare Mirrors**

Polarized Lighting

The technical development of a polarized headlight system consisting of polarizing filters on headlamps and a viewer filter on the driver's eyes was begun by Edwin Land in the 1940s. Although polarized lighting on automobiles is still not commercially available, extensive research was funded by the Federal Highway Administration (FHWA) in the 1960s. In reporting their research on polarized head lighting, Hemion, Hull, Cadena, and Dial (1971) describe the basic physics of polarized light. Ordinary light, including light from an automobile headlight, consists of electromagnetic waves that vibrate in all directions perpendicular to the direction of the beam (Figure 5). When ordinary light passes through a polarizing filter, all of the light waves are absorbed except for those vibrating in a single plane (Figure 6) and the light becomes (linearly) polarized. The polarizing axis of a filter is the orientation of the electric or magnetic field of the light waves that are able to pass through the filter (for example, 45 degrees with respect to vertical).

The polarizer — The polarizing filter, or polarizer, can be made in different ways. The original polarizers of the 1940s were made from plastic sheets that were stretched to give their molecular structure a preferred orientation. These polarizers decreased visibility because they were inefficient and blocked out too much light. In addition, some of the original versions of the sheet polarizer were prone to overheating and degradation. Since the 1940s, more efficient ways of polarizing light have been found, some of which are summarized by Duncan (1996).

Scotch optical lighting film (SOLF) — SOLF is constructed from a pair of plastic sheets, each with a sawtooth cross-section on one surface, so that the sawtooth surfaces of the sheets are mated

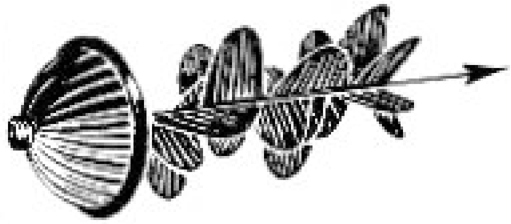

Figure 5. Ordinary Light produced by an automobile headlight.

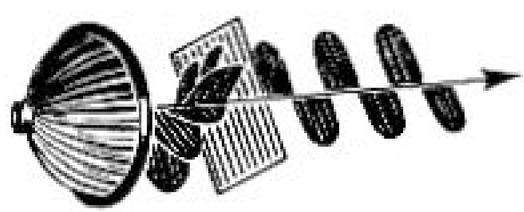

Figure 6. Plane polarized light produced by placing a polarizing filer in an ordinary light beam.

together to form grooves. Light polarized perpendicular to the grooves is transmitted and light polarized parallel to the grooves is reflected. While the original sheet polarizers absorbed light not matching the desired polarization axis, polarizers like SOLF redirect this light.

Liquid crystals — Liquid crystals with a helical structure are stacked into a filter so that the axis of the helix is perpendicular to the plane of the device. Liquid crystal filters are used to produce circularly polarized light, in which the plane of polarization rotates about an axis defined by the direction of the beam. Looking in the beam direction, the rotation can be either clockwise (left-hand circular polarization) or counterclockwise (right-hand circular polarization). Unpolarized light is a combination of right-hand and left-hand circular polarized components; when it passes through the liquid crystal filter, the component that is circularly polarized consistent with the curl of the crystal helix is reflected and the other component is transmitted. This type of filter will only affect light of a certain wavelength, letting all other wavelengths pass through unaffected. Therefore, in order to create a polarizer that will work for multiple wavelengths, different liquid crystal filters must be stacked together.

Corning Polarcor – Polarcor is a variation of the original sheet polarizers. It is made of glass that contains elongated submicroscopic silver particles that are aligned along a common axis. The particles absorb light that is polarized along the particles' long axis and that has a particular wavelength. Absorption depends on particle size and shape—more elongated particles absorb longer wavelengths of light. This technology has several advantages, including a large acceptance angle for light not hitting directly on axis and the capability to make a polarizer that operates on specific wavelengths.

Duncan (1996) summarized polarizer technologies (see Table 2, below) and rated them on a scale of 1 (poor) to 5 (excellent), according to the following criteria:

- Manufacturing complexity — A measure directly related to the cost of the product.
- Temperature sensitivity — The ability of the polarizing material to withstand high temperatures.
- Efficiency — How well the polarizer transmits desired wavelengths of light in the desired plane and blocks light of other wavelengths and other orientations. An inefficient polarizer will block too much light and so decrease visibility unless a high-intensity headlamp is used.
- Chromatic effects — The ability of the polarizer to be effective for light of all wavelengths.
- Angular effects —How much the degree of polarization changes when the angle of incidence is varied. Most filters produce maximum polarization when light strikes them at normal incidence.

Table 2. Relative Merits of Various Polarizer Technologies (Duncan 1996)

Technology	Manufacturing Complexity	Temperature Sensitivity	Efficiency	Chromatic Effects	Angular Effects	Total
Polaroid sheeting	5	1*	2	5	5	18
3M SOLF	2	5	5	3	3	18
Liquid Crystals	2	5	5	3	3	18
Polacor	5	5	2	5	5	22

* Duncan classifies the temperature sensitivity of the sheet polarizer as poor. This was the case when the idea was originally suggested in the 1920s, but by the time polarized lighting was tried in automobiles the heat problem had been resolved. With this marked improvement in temperature sensitivity, the Polaroid sheeting would have a score comparable to that of Polarcor.

The polarized headlight system — A polarized headlight system can improve visibility for drivers by decreasing the amount of light from oncoming headlights. For this system to work, both vehicles must be equipped with the proper hardware. In the following description of the system, the beneficiary will be referred to as the "driver" and the opposing vehicle will be the source of the glare.

- A polarizer is placed over the opposing vehicle headlights with its polarizing axis at 45 degrees from vertical.
- Another polarizing filter is placed in front of the driver's eyes with its axis parallel to that of the polarizer in front of the headlights. This polarizing filter is sometimes referred to as an analyzer.
- Both cars should have a polarizer and both drivers should have an analyzer.

Two types of analyzers were developed. One type, referred to as a visor, was a strip of sheet polarizer that was hung from the sun visor in such a way that its bottom edge intersected the line of sight from the driver to oncoming vehicles. When there was no visible opposing vehicle, the driver could look under the visor. Another type of analyzer took the form of either full- or half-glass spectacles. The half-glass type operated like clip-on sunglasses and could be used in the same way as the visor. That is, drivers could look through the analyzer when a vehicle was approaching and through the bottom, unpolarized portion when the analyzer was not needed. The half-glass can be fitted over prescription glasses or over a pair of neutral glasses with no optical function (see Figure 8 below). The full-glass type, for use by passengers, is functionally identical to sunglasses.

If two cars are equipped in exactly the same manner, then the orientations of the analyzers and polarizers will be the same when the two cars are facing in the same direction. However, when the two cars approach each other facing in opposite directions, then the orientation of the analyzer and polarizer for one car will be perpendicular to those in the other car. This is illustrated in Figure 7.

The polarizing system reduces glare in the following way:

1. Light from the opposing headlamps of an approaching car will pass through the polarizer in front of that car's headlamps. As explained above, the orientation of the polarizer in front of the opposing car's headlamps is perpendicular to the orientation of the analyzer in front of the driver's eyes, since the cars are facing in opposite directions.

2. Therefore, the light coming from the opposing headlamps will, upon passing through the polarizer, become polarized in a direction perpendicular to the polarizing plane of the driver's analyzer.

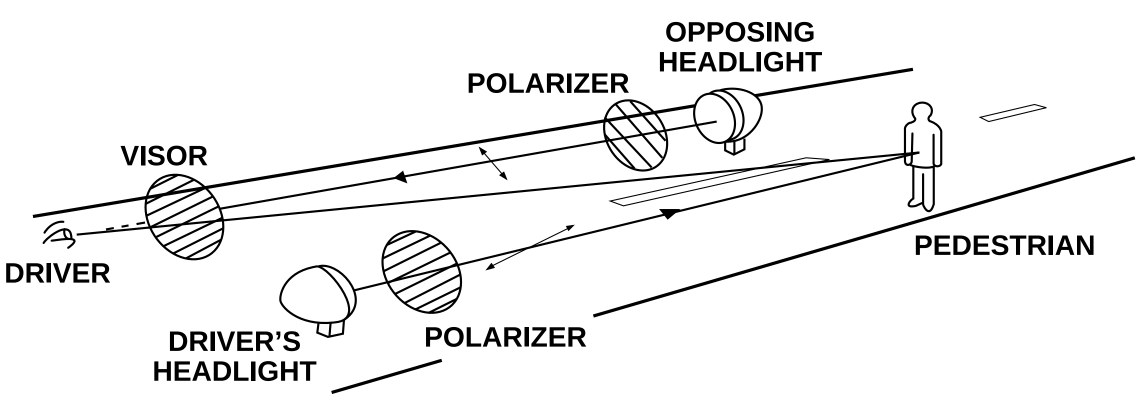

Figure 7. Illustration of Polarized Lighting System

3. Since the driver's analyzer is oriented perpendicular to the plane of the polarized light coming from the opposing car's headlamps, it will not allow this light to pass through and reach the driver's eyes.

Note: Light from the driver's own headlights will be reflected from objects such as pedestrians and road signs and return through the driver's analyzer, which is oriented to allow light polarized in the same direction as that from the headlights, making the objects readily visible.

According to Schwab and Hemion (1971), the polarized headlight system is the most promising and most likely system to solve the night visibility problem. After reviewing studies that tried to determine means by which night visibility could be improved, Schwab and Hemion (1971) concluded that:

1. "...the [polarized headlight] system is technically and economically feasible in regard to today's vehicle population;"

2. "the system would be advantageous in terms of improved visibility with less glare for motorists;"

3. "the results of the use of such a system would be increased vehicular control, safety, and comfort and probably improved traffic flow and utilization of highways at night."

Dynamic Polarization is a modification described by Duncan (1996). In this system, the headlights are polarized as described above, but the analyzer is an electro-optical device that is activated whenever incident polarized light is detected. Unlike static polarization systems, this system offers advantages to those using it even when polarization is not in universal use. Since the analyzer would normally (in the absence of polarized light) pass all polarizations, objects would be just as visible as at present without any increase in headlight output. Duncan points out that the technology that most contributes to making this approach possible is the so-called "polarizer on demand": "This is one of several liquid crystal devices that are clear in one state, i.e., they pass all polarizations equally and pass or block a particular polarization in the other state."

Because it does not require any increase in headlamp intensity, use of dynamic polarization would cause no increase in rear-view mirror glare. Of course, if the source of the glare were polarized lighting, it could be filtered by the analyzer as well. The system could also be designed to reduce the backscatter, which limits visibility in fog. This system might also overcome some of the implementation problems discussed below. However, it appears that there are technological and human factors issues which need to be addressed before dynamic polarization can realistically be compared with other countermeasure alternatives.

Research

The feasibility of polarized headlighting was extensively researched by the Federal Highway Administration in the 1970s. These studies hoped to answer three questions about nighttime visibility and polarized headlights: 1) Do drivers using conventional high beams and low beams have a problem with visibility distance that a polarized system would resolve? 2) How would visibility be affected during a transition to polarized headlights, when not all vehicles have the polarized system? 3) Would the benefits of polarized headlights outweigh the problems associated with the system in a "real world" situation?

The studies of visibility distance when using conventional headlights were summarized by Schwab and Hemion (1971). These studies involved determining the distance ahead at which three different targets first became visible to subjects using four different headlighting systems: conventional low beam, conventional high beam, polarized high beam with analyzer, and polarized high-intensity beam with analyzer. The test was done both with one opposing vehicle and with no opposing vehicles. When an opposing vehicle was present, both vehicles were equipped with the same type of headlighting system.

The studies found that the visibility available to the driver in meeting situations with conventional high and low beams was unsatisfactory because it did not provide enough time to perform an evasive action if one were needed. In the opposed mode, use of polarization increased the visibility distance compared to conventional headlights, regardless of the target or of the intensity of the lamp used with the polarizer.

In order to address the question of visibility during the transition period, Hemion (1969a) conducted experiments to determine the driver's ability to see when vehicles equipped with polarization systems met vehicles not so equipped. Hemion measured disability veiling brightness and target detection distance for ten different cases, which are summarized in Table 3. Each case was ranked in terms of glare and relative visibility, with 1 being the best rank and 10 the worst.

Hemion observed veiling brightness levels that ranged from 0.0046 foot-lamberts, in case 9, to 4.9 foot-lamberts, in case 1A. In only one case was the visibility reduced measurably from the normal low beam-to-low beam meeting, namely when the glare car was on low beam and the subject car was on polarized low beam with an analyzer in use. Hemion surmised that this case would be rare in practice because the subject driver would realize that the opposing car did not have polarized lights and would stop looking through the analyzer. Visibility was improved in four of the nine cases, all involving a modified vehicle, compared to unmodified high beam-to-high beam or low beam-to-low beam meetings. Hemion concluded that, "It appears that improved visibility of roadside obstacles will be achieved from the beginning of the period of transition to polarized lighting with greater and greater improvement as more vehicles are converted."

Finally, while planning a large-scale public test of polarized headlights that was never performed, Hemion et al. (1971) conducted a small-scale test, consisting of approximately 120 drivers and observers on a 40-mile test loop of two-lane, rural, unlighted roads. The results confirmed that for the "average" motorist, the benefits of improved vision and nighttime driving comfort

Table 3. Target Visibility (Hemion 1969a)

Mode	Glare Car	Subject Car	Relative Glare	Relative Visibility	Mean Detection Distance, feet
1A	HiB*	HiB	10	5	305
1B	LoB	LoB	8	7	255
2	HIP w/A	HIP w/A	2	2	469
3	HiB	HIP w/A	9	9	208
4	HIP w/A	HiB w/A	3	3	442
5	LoB	LoBP w/A	5	10	146
6	HIP w/A	LoB w/A	4	8	231
7	LoB	HIP wo/A	7	1	479
8	LoB	HIP w/A	6	4	433
9	LoBP w/A	LoB w/A	1	6	293

*HiB – High Beam, LoB – Low Beam, HI – High intensity, P – Polarized, w/A – with analyzer for driver, wo/A – no analyzer for driver would outweigh the deficiencies presented by the polarized headlight system.

Advantages

There are numerous advantages to a polarized headlight system, all of which are just as applicable today as they were thirty years ago, when the research was performed.

Excellent illumination — While an increase in headlamp intensity is necessary to offset the attenuation of the analyzer, even higher intensities than required are permissible because glare from oncoming drivers is not a concern. Polarized headlamps could also be aimed further upward so that they can intercept obstacles in the roadway at a greater distance than the current system of headlights, which must be aimed below the horizontal to reduce glare.

No blind driving zone — During a meeting situation, the driver often cannot see beyond the opposing car's headlights. This is referred to as a blind driving zone and, according to Land (1948), drivers habitually drive into this zone on faith, hoping there is nothing in the road. With the polarized system, there is no blind driving zone.

Long visibility distances during a meeting situation — Schwab's review of reports found that most people overdrive their headlights at night. This means that, in a meeting situation with another vehicle, drivers often cannot see far enough to be able to stop for an obstacle in their path. Polarized headlights increase the visibility distance and therefore increase the detection distance of such targets. (Hemion 1969a)

Insensitive to headlight aiming, vehicle loading, horizontal and vertical curvature — As just described, the polarized headlight system depends on keeping the driver's analyzer perpendicular to the polarizer on the opposing vehicle's headlamps. However, during vehicular roll, the analyzer and the headlamp polarizer will rotate away from being perpendicular to each other and some light will be able to leak through. A study by Adams (1971) indicated that this leakage had an insignificant effect on detection distances during meeting situations.

Proper use is easy to learn — In small-scale studies of polarized headlights, subjects had no problems learning how and when to use the analyzer. To look through or past the analyzer, only minor head movements were necessary.

Disadvantages

The disadvantages associated with polarized headlights seem to be minor, and a solution to each is presented below. The only major disadvantage of the system is the difficulty in implementing it.

Headlamp intensity must be increased — According to Duncan (1996), light intensity reaching the eye will decrease by 50%, even with a perfect analyzer. This reduction also applies to ambient light that is not polarized. The proposed strategy for dealing with this problem is to increase headlamp output by a factor of two.

Haze of approaching car is not visible — Haze, which warns of the approach of a car over a hill or around a curve, is not visible if the analyzer is used. To continue to observe haze, the driver can refrain from using the analyzer unless polarized headlights are in view.

Effect on distance perception of approaching cars — The effect of polarized light on a driver's ability to judge the distance to oncoming vehicles is largely unknown. Hemion (1971) expected that once people gain experience with seeing approaching cars that are equipped with a polarized headlamp system, they will adapt to judging speed and distance with the system and the magnitude of this disadvantage will be reduced. All of the drivers in Hemion's (1971) study encountered an oncoming vehicle with polarized headlights, but none of them mentioned distance perception as a problem. Still the effect of a polarized system on driver judgement in passing situations should be studied.

Effect on visibility of Traffic Control Devices — The effect of the analyzer on the visibility of traffic signals and hazard warning lights is largely unknown and should be investigated.

Implementation — The main factor that has restricted adoption of polarized headlights is the absence of an efficient method to implement the system. There are two principal concerns:

(1) How will the change to polarized headlights be motivated?

(2) What operational problems will arise during the transition period, and how will these affect public opinion?

These concerns are discussed in more detail below.

How would the change to polarized headlights be motivated?

When used as a glare countermeasure, polarized headlights and analyzers constitute a cooperative system, with effective operation dependant on its use by all people. For this reason, the system will most likely have to be implemented by mandate and/or promoted by advertising. Advertising may be ineffective because, as Duncan (1996) observed, "it is easier to market a product or service to a public that perceives a need than to implant the idea of need in the minds of the public."

Another consequence of the cooperative nature of the polarized system is that there is no competitive incentive for a car company to be the first to install the system. If the system is introduced on only one make of cars, it will only be effective when it meets cars of that make.

What operational problems will arise during the transition period and how will these affect public opinion?

According to Hunt (1948), an additional concern with implementing the polarized headlight system is that there will not be a smooth transition period from the current system. Obviously, not all cars can be equipped at once, so there may be a lengthy period of mixed use of polarized and non-polarized headlights. During this transition period, some situations could arise that may hurt public opinion of polarized lights. Drivers who paid for the polarized headlight system will probably be disappointed in the long delay in receiving full benefits from the system. Drivers who had not upgraded to the polarized system could create glare for polarized drivers by misusing high beams, while protecting themselves against the polarized beam by purchasing an analyzer. Drivers with polarized headlights could cause glare by using high beams when meeting cars without the new system. Public resentment against polarized lights could build up during the transition.

Summary

The polarized headlight system appears to be a cost-efficient means of solving the glare problem. Not only does it eliminate glare from oncoming vehicles, but it provides a solution to the more critical problem of limited sight distance at night. With one technological stroke, a quantum leap in highway safety could be accomplished. Whether or not the costs can be justified on the basis of glare reduction, the benefits of improved vision for night driving should be substantial. Still, the problems associated with implementation need to be addressed.

The major drawback to polarized headlights is that installing them on a vehicle helps only the oncoming driver, not the person who paid for them (at least, until all cars are so equipped). How can a conversion be accomplished quickly and universally? How can misuse of high beams during the conversion period be controlled? To answer these questions a large-scale experiment should be conducted similar to the one proposed by Hemion et al. (1971).

Night-Driving Glasses

A distinction must be made between night-driving glasses that are aimed at attenuating night myopia and those marketed specifically as roadway glare reducers. The former are untinted and include a small diopter lens correction (like that in prescription lenses) to counteract the intraocular lens's natural inclination to return to its tonus, or resting position, in the absence of accommodative stimuli (i.e., something to focus on). At night, many people with normal vision tend to become myopic and many myopes tend to become even more nearsighted (Leibowitz and Owens 1976).

Night-driving glasses for glare reduction are structurally and functionally very similar to sunglasses and, in fact, some models are merely a remarketing of what was originally a pair of sunglasses. Like sunglasses, these glare-blocking glasses work by filtering light prior to its reaching the driver's eye. Many models use color filters to eliminate short-wavelength or "blue" light and so have a yellow tint. Some are full-sized, some fit over prescription glasses, and others are smaller, filtering only a thin strip of light in the upper portion of the eye. A unique model developed in the 1950s (Bryan 1962), called "Nite-Site," used a green, ring-shaped filter that was affixed to prescription lenses so that the observer looked though the clear center. The filter was purported to "...cause a shadow effect to fall across the pupil to eliminate the oncoming glare of headlights...." Another lens, described by Adrian (1979), had a clear circular center large enough to transmit light with a glare angle of less than 5 degrees surrounded by a shaded area that gradually increased in transmission according to the glare angle squared, so that the wearer could view glare from oncoming traffic through the shaded area. In most cases, the shading was not uniform over the ring, but only covered the sector in which glaring headlamps usually occur.

Another type of night-driving glasses, shown in Figure 8, has been introduced by Glareblockers™. Their product is an ultraviolet-filtering polarizing plastic that attaches to the user's own eyeglasses, covering the top half of the lenses, and is adjustable for proper fit. The design is similar to the half-glass analyzer used in the studies of polarized headlights reviewed above. With a half-glass analyzer, the user can turn filtering on and off with a slight tilt of the head, much like using bifocals. The product provides glare control on demand, and, when glare control is not needed, allows the user to normally look through his own glasses.

Figure 8. Half-glass analyzer permits normal or filtered view.

The basic idea behind all glare-reducing night-driving glasses is that a reduction in the amount of light at the eye will reduce glare. This reduction could be accomplished by using simple neutral density (n.d.) filters, which filter all wavelengths equally and cause minimal color distortion. Why, then, are most night-driving glasses designed to selectively filter out the shorter electromagnetic wavelengths, in the blue and near-ultraviolet spectral range? Below, the theory behind this selective filtering will be evaluated both from an empirical and a physiological/perceptual perspective; first, the claims made by the distributors of these devices will be explored.

Benefits Claimed by Manufacturers — According to the manufacturers' or marketers' claims, glare-blocking glasses solve problems associated with oncoming headlamps ("especially the new halogens") and with lack of contrast that causes disability glare. They are also said to improve general nighttime vision and night driving safety, reduce glare effects associated with aging and cataract development, reduce eye fatigue, and help drivers keep their "eyes on the road." These glasses are also "cool looking." The "Blue Max" glasses "block uncomfortable blue light which causes hazy vision." All these glare blockers are "good for people with sensitive eyes." "Confusion is gone. Confidence is restored." They are also said to improve vision on roads with overhead lighting.

Federal Trade Commission (FTC) Ruling Number 952 3041 — In 1997 the FTC ordered a nighttime glare-reducing glasses direct marketer to "cease and desist from representing, in any manner, directly or by implication, that such product makes night driving safe or safer; or such product improves night vision." The marketer, Nationwide Syndications Inc., of Barrington, IL, reached a settlement wherein they were prohibited from using the "NightSafe" name and agreed to pay $125,000 in consumer compensation. What the FTC essentially said was that Nationwide Syndications had no evidence to back up its claims, not that the glasses did not work. It appears that this ruling has not stopped other distributers from making identical claims for essentially the same product.

Research Findings

Glare Sources — Night-driving glasses are said to attenuate glare from two sources. Misaimed and high-beam headlamps seem from the promotional literature to be the biggest perceived problem. The introduction of high-intensity discharge (HID) lamps and the proliferation of sport utility vehicles (SUVs) and other vehicles with high-mounted headlamps are seen as increasing the problems associated with nighttime headlamp glare (daytime running light glare is a different issue entirely). The second glare source of concern is luminaires, otherwise known as overhead lamps or street lighting. The impact of overhead lighting on glare (and glare mitigation) has already been treated in detail in a previous section of this report. For this reason, and because overhead lighting is a secondary concern for users of night-driving glasses, the remainder of this section will concentrate on headlamps.

Headlamps — Headlamp contributions to disability and discomfort glare are treated in detail in other sections of this report, but it may be useful to revisit the issue of color temperature. With the recent introduction of HID headlamps, drivers are encountering not only the yellow/white of halogen headlamps but also a bluish-white from the higher color temperature of the HIDs. The color temperature of xenon HID headlamps ranges from 4000 to 4500 Kelvin (K), which is much closer to that of sunlight (4500–5000 K) than are halogen lamps, which fall around 3200 K. Other headlamps look like HID headlamps but are not; these are the so-called "ion blue" or "diamond blue" halogen bulbs, which are actually halogen bulbs with a blue coating that reduces overall light output.

Do the new bluish-white HID headlamps result in increased glare problems, as suggested by glare-blocking glasses distributers? There is some evidence that they may. Flannagan, Gellatly, Luoma and Sivak (1992) found that dim HIDs produce as much glare as bright halogens—more specifically, that higher levels of light from halogen lamps produced no more discomfort than lower levels from HID headlamps. This finding is consistent with studies of the effects of wavelength on discomfort glare discussed later in this section. The effects of the shorter-wavelength HIDs on disability glare will also be discussed below.

Yellow Lenses and The Human Visual System — One possible reason for using yellow filters (blue light blockers) is that the blue light may be scattered more within the ocular media than the longer-wavelength yellow or red light. Direct evidence that longer-wavelength light is less susceptible to absorption and scattering by small particles is seen at every dusk and dawn, when the sun appears as an orange or deep red ball because of the longer path length of those colors through the atmosphere. As sunlight traverses the earth's atmosphere at the oblique angles found at sunset and sunrise, airborne particles scatter the blue wavelengths, leaving the reds relatively unaffected. The same phenomenon occurs with sound: Higher-pitched sounds die away at shorter distances than lower-pitched (longer-wavelength) sounds when there are obstacles between the source and the receiver, because the amount of scattering from atmospheric particles increases as the wavelength decreases. This phenomenon is why foghorns have such a low pitch. However, as Blackwell (1954), citing Fry (1953), stated, "The majority of scattered light within the eyeball is due to large particles which scatter nonselectively [with regard to wavelength]." That is, all colors scatter in the eye to the same degree, so that—with regard to scattering in the optical media, at least—

there is no glare-reducing benefit to filtering out certain wavelengths. Blackwell's statement is supported by Ucke (1973) who measured scattered light of different wavelengths directly at the retina. Smart (1970) compared the effect of blue, red, green and white light sources on disability glare; while he found some small and interesting differences in the laboratory, he concluded that glare in the real world could not be mitigated by manipulating lamp color.

A second theory used to justify the filtering out of blue light is based on chromatic aberration. Focusing of light in the eye depends on refraction, and refraction in the eye's lens—as in most lenses—depends on the wavelength of the light. As a result, light of different colors is focused differently on the retina, a phenomenon known as chromatic aberration. Blue light is focused "near," red light is focused "far" and green light falls somewhere in between. Because of chromatic aberration, when red words are printed on a saturated blue background a three-dimensional effect is seen, a phenomenon known as the chromatic depth effect. Could chromatic aberration be a problem that would be ameliorated by using yellow-tinted nighttime driving glasses? Probably not. To begin with, the macula lutea (literally, yellow spot) which covers the retina's sensitive central visual area, the fovea, absorbs much of the blue light, helping to alleviate this problem naturally. Furthermore, as pointed out by Blackwell (1954), acuity might be affected by chromatic aberration, but acuity is not as important in nighttime driving as are target detection and time-to-contact estimations (estimations of distance and speed), neither of which ought to be compromised by chromatic aberration.

If neither blue-light scattering nor chromatic aberration justifies color filtering, why not use neutral density filters, which would maintain color balance? The answer might lie in discomfort glare. Blackwell (1954) found that yellow-tinted lenses produce a lower subjective impression of discomfort glare than do neutral density filters, even when both allow equal light transmission. Further evidence is provided by a study on headlamp color by the Institute for Road Safety Research (1976). Although it found no perception-based reason to recommend yellow over white headlamps, the study concluded that "minimal side effects (discomfort glare) were experienced which might indicate a preference for yellow light." Perhaps the final word on this issue was an in-depth study (Flannagan, Sivak, and Traube 1994), which found a U-shaped relationship between discomfort glare and wavelength, with long-wavelength (650 nm) and short-wavelength (480 nm) light producing the greatest discomfort and intermediate wavelengths (centered at 577 nm) producing the least. In terms of colors, yellow was the most comfortable and red and blue were the most uncomfortable, with blue being even worse than red.

A convincing argument could be made that discomfort glare might indirectly reduce visibility. That is, if an observer is made uncomfortable by a glare source, his performance on visual tasks might suffer, even though there is no direct disability glare. This might result because of reduced alertness caused by fatigue or changes in driver fixations caused by glare avoidance. Theeuwes and Alferdinck (1996), for example, found that subjects were less willing to look at a light source when illumination was higher.

Two footnotes are worth reporting here. First, the human eye develops opacities as it ages in which the lens progressively yellows. Exposure to ultraviolet radiation is considered to be partially responsible for this "natural effect of aging." Second, tinted glasses can have unintended consequences—as discovered by the Maryland Department of Transportantion in 1997, when they found that neodymium sunglasses with a notch filter in the amber color range between 580 and 600 nm completely blocked out yellow LED warning signs and traffic signals. These kinds of glasses have since been outlawed by a change in ANSI standard Z80.3 for sunglasses.

Glare and Reduced Visibility — The idea of reducing roadway glare by using special glasses is not new; in fact, fifty years ago Lauer (1951) conducted an extensive study of the effect of color filters on visual acuity in the presence of a glare source. Lauer found no difference in performance among the 15 color filters he tested (which included n.d., purple, blue, green, yellow-orange and red); all resulted in significant loss of acuity under glare conditions. The study concluded, “Although some colors reduced glare, they also reduced acuity to the same degree.”

A study of two optical filters used in glasses to reduce driving glare in the 1950s (Blackwell 1954) evaluated the effect on threshold contrast for one “pale yellow” filter (luminous transmittance of .87 and one “amber” filter (luminous transmittance of .69). The study found that glare reduced target detection but so did the tested filters, and the use of filters in the presence of glare did not produce a compensatory result. In fact, it was more difficult to detect targets in the presence of glare when wearing the glare blocking filters than when not. Translated to the highway, these laboratory findings predict that not only will the filters reduce detection distances, but the reduction will be greatest under conditions where detection distances would be short even without the glasses. That is, the filters would make a bad situation even worse. Detection distances would be reduced 10% to 20% with a pale yellow filter and 30% to 40% with the amber filter under twilight driving conditions, without headlamps from the observer’s vehicle. The losses would be somewhat less if the observer’s headlamps were activated.

Disadvantages

There are two potential disadvantages to fully tinted glare-blocking night-driving glasses. First, the user might have a sense of improved nighttime vision disproportionate to any actual gains in visibility. Such an exaggerated sense of improved vision might tempt the user to “override” his visual capabilities, driving at speeds in excess of the actual stopping distances given by visibility and natural driving conditions. Second, whenever light is blocked, the visibility of roadway obstacles is reduced. The glasses lower the overall roadway luminance seen by the observer (although contrast remains constant), and therefore reduce visibility. It might be argued that this reduction in visibility is compensated for by the reduction in disability glare, but there is no evidence to support this.

Advantages

There are several ways that nighttime glare-blocking glasses might improve driving safety. None of these possible advantages have the empirical evidence necessary to support the continued use of these devices.

First, glare-blocking glasses reduce overall illumination, thereby reducing glare in the same way as daytime sunglasses. Unfortunately, the light emitted or reflected from all other roadway characteristics is also reduced, reducing target detection over and above the reduction caused by the glare source itself. Other eyeglasses, such as the “Nite-Site,” that were designed to filter only the small portion of the driving scene that contains the glare source, will still necessarily obscure objects outside their target areas, because the glare source is in constant relative motion and is continually changing in retinal image size as it approaches the observer’s vehicle.

Second, glare-blocking glasses might selectively eliminate those wavelengths of light which create the biggest glare problem for human observers and improve visibility by either reducing chromatic aberration or decreasing intraocular scattering. Research shows, however, that chromatic aberration is not a significant factor in nighttime driving and that intraocular light scattering is not wavelength dependent.

The third possible advantage is perhaps the most plausible. There is good empirical evidence that discomfort glare is reduced by yellow-tinted glare blockers when an observer is faced with a mainly white glare source such as a headlamp. Discomfort glare might have an indirect effect on object detection, because an observer who is uncomfortable might perform worse on visual tasks. The study by Blackwell (1954) does not support this claim, but Blackwell’s data were collected in a laboratory setting, and drivers in a roadway environment might behave differently. Blackwell’s subjects, for example, were asked to peer through the glare source to detect the targets, whereas vehicle operators actually on the highway are encouraged to “look off to the right and down at the edge line” as oncoming vehicle headlamps approach. The issue of how discomfort glare affects visual performance would benefit from additional research.

The introduction of the Glareblockers™ product, which provides glare control on demand, brought another dimension to the design of night-driving glasses. This type of half-glass analyzer could provide a real advantage if it is used only when the discomfort is so great that the choice is between looking to the side, so the road is seen only with peripheral vision, and looking straight ahead with foveal vision reduced by glasses. Whether drivers would restrict their use of a half-glass analyzer to such worst-case situations is unknown. The drivers most likely to benefit from this type of glasses are those with severe sensitivity to glare; these drivers may be candidates instead for restricted night driving, as discussed elsewhere in this report.

Summary

On balance, reasoning based on solid physiological and perceptual concepts and backed up by almost 60 years of good empirical research yields no real support for the use of fully tinted glare-blocking glasses as a means of achieving safer nighttime driving. As Lauer firmly stated back in 1951, "...any media introduced between the eye and a stimulus object or situation on the roadway as a means of reducing glare is not to be recommended for night-time or any other conditions which lowers acuity when maximum visual efficiency is desired." The half-glass analyzer offers the possibility of improving safety if properly used, but the research has not yet been done to evaluate whether this possibility can be realized.

Glare Screens

On divided highways without independent alignment or large medians, glare screens placed in the median of the roadway could be a cost-effective way to reduce glare from opposing traffic. Screens can improve safety in temporary work zones, where lanes can be narrow and only a concrete barrier separates opposing traffic. Under these circumstances, blocking glare from oncoming headlights will dramatically increase the visibility of the concrete barrier and the delineation of the lane ahead.

The National Cooperative Highway Research Program Report 66 (NCHRP-66 1979), a report of the Transportation Research Board, includes descriptions of the different types of glare screens and the advantages and disadvantages of each. NCHRP-66 defines a glare screen as ". . . a device placed between opposing streams of traffic to shield drivers' eyes from the headlights of oncoming vehicles. . ." (pg. 2). A glare screen can be any type of object of a certain width and placed at a certain spacing that will prevent glare from reaching drivers' eyes. The object may be opaque or have intermittent openings that allow a view of the opposing lanes while at the same time screening out light at angles less than 20 degrees from the driver's eye.

To be effective, glare screens should:

- Reduce a large portion of the glare
- Be simple to install
- Be resistant to vandalism and vehicle damage
- Be repaired quickly and safely
- Require minimal cleaning and painting
- Accumulate a minimal amount of litter and snow
- Be wind resistant
- Have a reasonable installation and maintenance cost
- Have a good appearance
- Allow for emergency access to opposing lanes

There are three types of glare screens, labeled Type I, Type II, and Type III. A Type I glare screen is a continuous screen that blocks light from all angles. A Type II screen is a continuous screen of an open material that is opaque to light coming from angles of zero to 20 degrees from the driver's eye and becomes increasingly transparent for angles beyond 20 degrees. A Type III screen is made up of individual elements that will block light coming from angles of zero to 20 degrees from the driver's eye while providing clear visibility beyond 20 degrees. A plan and elevation view illustrating the concept of each type of glare screen is shown in Figure 9.

Examples of Type I glare screens include earth mounds and concrete barriers. Earth mounds are used in areas with wide medians and excess cut material. Usually in these areas grades and cross-sections can be modified to leave or build this excess earth in the median to block glare. Concrete glare screens are usually provided by simply extending the height of a standard concrete barrier enough to block light from opposing vehicles.

Type II glare screens include expanded metal mesh, knit polyester fabric, and fencing. Expanded metal mesh is the most widely used type of screen. It is usually manufactured from steel or aluminum sheets. Parallel slits are cut into these sheets and then the sheets are stretched until the slits form a diamond pattern. The metal

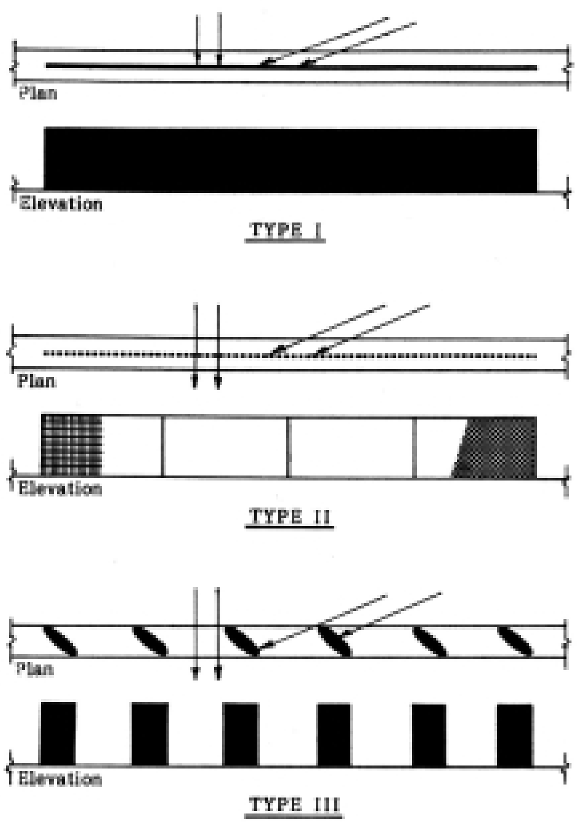

Figure 9. Plans and elevations of glare screen types I, II, and III (NCHRP 1979).

Figure 10. Paddles at angles less than 20 degrees appear to present a solid screen from the driver's view. (Courtesy glaregaard.com)

between the slits twists at an angle to form a screen. Knit polyester fabric also works as a glare screen by diffusing light rather than blocking it. Chain-link fences are effective Type II glare screens when the patterns of the wires have a spacing less than one inch.

The most common kind of Type III glare screen is manufactured by placing individually-supported paddles at intervals so that they will block light from opposing headlights. An example of these paddles is the Glare Gaard, elliptically shaped 25-inch blades made out of thermoplastic polyolefin (TPO) that attach via anchor bolts to a concrete barrier (see Figure 10).

Other types of glare screens not included in any of the above categories include plants and guardrails. Plants are suitable glare screens on curves in wider medians as part of a general landscaping effort. Back-to-back guardrails will block glare, but they may not be effective in blocking all of the light from an oncoming vehicle since they are only 27 to 33 in high. Some characteristics of the different types of screens are given by NCHRP-66 and are shown in Table 4.

NCHRP-66 (1979) recommends that before installing a glare screen, "the manner in which various types of screens reduce glare and affect

Table 4. Characteristics of Different Types of Glare Screens. (NCHRP 1979)

Characteristic	Type I	Type II	Type III
Prevent gawking accidents	yes	no	no
Prevent pedestrian crossings	yes	yes	no
Prevent slush & other objects from being thrown into opposing lane	yes	yes	no
Permit police surveillance of opposing lanes	no	yes	yes
Permit access to opposing lanes by emergency personnel	no	no	yes
Permit scenic viewing	no	yes	yes

both visual and physical access to opposing lanes should be considered. . ." (p. 4). For example, using an opaque screen may prevent drivers from becoming distracted by happenings in the opposing roadway, whereas using a Type II or Type III screen may provide a limited view of the opposing lanes, which many feel is necessary for law enforcement and emergency services.

Research

As mentioned earlier, we seldom hear of a traffic accident caused by glare. Therefore, it is difficult to relate any change in accident rate to the installation or use of a countermeasure such as a glare screen. Compounding this problem is the random nature of accidents and the complexity of accident causes.

Despite these problems, accident data in many states have been collected after the installation of a glare screen. NCHRP-66 summarizes studies that were done in California, Indiana, Michigan, New Jersey, Ohio, Pennsylvania and England. The New Jersey, Ohio, and Pennsylvania studies showed reductions in nighttime accidents in sections where glare screens were added, but NCHRP-66 made no conclusive statements.

Advantages

- Effectively reduce glare from oncoming vehicles
- Simple to install, minimal maintenance, and quick and safe to repair
- Installation can be limited to specific problem areas such as on horizontal curves.
- Reasonable cost

Disadvantages

- If the median is narrow, use of a glare screen requires some type of barrier on which the glare screen can be installed.
- Unless there is a sufficiently wide shoulder, a lane of traffic must usually be closed for installation, repair, or maintenance.
- The screen is effective only where the user's vehicle, the intermediate median and the approaching vehicles are on the same or near-level plane. Measurements made with an experimental glare screen installation on the Schuylkill Expressway (now I -76), near Conshohocken, PA, showed that the glare from cars passing one vertical curve would have required a screen 40 ft tall to block the glare from a car at the next crest (Schwab 2000). Glare screens do not work well with rolling alignments, which have a significant amount of vertical curvature.

Summary

Since glare screens have no benefit other than reducing glare, their application is limited to high-traffic locations where glare is particularly disturbing and continual. Unlike wide medians and independent alignment, glare screens will not reduce the seriousness or the frequency of accidents, except for those accidents directly resulting from glare itself. However, at locations where glare is a serious or habitual problem (as is often the case in temporary workzones), glare screens provide an inexpensive solution that may be justified on the basis of expected glare-related accidents alone.

Anti-Glare Mirrors

The purpose of anti-glare mirrors is to achieve a balance between rearward visibility and protection from glare. Anti-glare mirrors are available in either of two general designs: the dual-setting, prism-type mirror and the variable-reflectance electronic mirror. Two other designs using completely different technology have been patented and are under development and evaluation; these will be discussed briefly at the end of this section.

Prism Mirrors

Prism-type rear-view mirrors have been standard equipment on U.S. cars for more than thirty years, and virtually every driver is familiar with their use. Prism mirrors change reflectance when the driver manipulates a lever mounted on the mirror. The reflectance at the anti-glare setting is only 4%. The two potential dangers with this type of mirror are that drivers may neglect to change the mirror back from the anti-glare setting and that the anti-glare reflectance may be too low. The reason that prism mirrors reflect only 4% when tilted is that this is the reflectance of a plain sheet of glass or plastic in front of a dark surface. The prism mirror has an outside cover glass with a movable mirror behind it. In the normal position, the highly-reflective mirror is parallel to the cover glass and transmits its reflection of the view from the rear of the vehicle—a relatively bright scene. In the anti-glare position, the mirror surface is angled so it picks up the image of the inside of the vehicle roof, which is a dark surface; the rear-view reflection the driver sees comes only from the cover glass, which has 4% reflectivity. It would be very difficult and much more expensive to get a higher reflectivity from this type of rear-view mirror design.

Electrochromic Mirrors

Electrochromic mirrors overcome the disadvantages of prism mirrors by providing continuous levels of reflectivity and automatic control. These mirrors automatically darken to reduce glare from the headlamps of vehicles approaching from the rear. The brighter the glare, the darker the mirrors become, without the driver having to take any positive action. These mirrors are often optional equipment, at a cost from $70 to $100, and are currently installed in very few vehicles; however, the market is rapidly expanding. Two manufacturers (Gentex and Donnelly) now manufacture both planar and convex driver-side and passenger-side electrochromic mirrors. The number of vehicles for which electrochromic mirrors are available continues to grow.

Photochromic Mirror

A new technology, proposed by a company named Quantics, offers a method of blocking only intense light rays, allowing dim rays to go through unattenuated. This differs from electrochromic mirrors, which reduce the brightness of the entire image. If successful, the new photochromic technology would allow rear-view mirrors to remain clear while blocking headlight glare.

A photochromic device includes an internal focal plane onto which a real image is projected. A light-sensitive “photochromic” layer that darkens in the presence of intense light and returns to clear when the light dims is inserted into the focal plane. Bright objects in the field of view generate a pattern of bright spots in the focal plane; in response, a pattern of dark spots appears on the photochromic material. Bright rays are self-attenuated because they go through the same dark spots that they create, but dim rays do not darken the photochromic layer and are not affected. The result is a clear field of view with only bright objects attenuated. Variations of the technology have been proposed to improve response time (to milliseconds or less) and to make the unit more compact by utilizing prisms or mirrors to fold the optical path.

Quantics has been funded by a series of small business grants from NASA, the Department of Transportation and the National Research Council. The company has secured patent rights for this technology and has built a proof-of-concept prototype that is available for demonstration.[1]

Neodymium Rear-view Mirror

Another new technology (Karpen 1998) would construct the rear-view mirror with glass containing neodymium oxide, a rare earth compound that filters out yellow light (this technology also underlies the color-corrected headlamps discussed earlier in this report). Karpen claims that the elimination of excessive yellow light lessens eyestrain and reduces discomfort from conventional headlights reflected in the rearview mirror. Contrary to the findings of Flannagan et al. (1994) discussed above, Karpen claims that yellow light is the source of most visual discomfort to a driver.

Pure neodymium oxide has a very narrow absorption band, but using the compound as a dopant in mirror glass results in a wider spectral region of absorption. Karpen cites a number of independent research studies that demonstrate the absorption by neodymium oxide glass of yellow light between 568 to 590 nanometers, and document the effects of this absorption: most colors become more saturated and there are a number of color shifts; for example, orange is shifted toward the red. A study of low-vision patients found more-accurate color rendering and an improvement in visual acuity and contrast, as well as a reduction of eye fatigue.

In a neodymium mirror, the light from following vehicles would pass through the neodymium glass to the silvered back of the mirror and be reflected back to the driver with a unique spectrum that Karpen claims will promote visual acuity in darkness by emphasizing the contrast-producing red and green light, and, at the same time, reduce the discomfort produced by yellow light.

Research

Olson and Sivak (1984) conducted studies of disability glare and discomfort glare, as well as the transient effects of mirror glare, with the interior mirror in the high-reflectance (not anti-glare) position. Glare levels under 1 lux, thought to represent low beams at 90 m or high beams at 300 m (based on data from Adler and Lunenfeld 1973), had a minor effect on visibility, but disability increased rapidly when illumination was increased above 1 lux. Even with the interior mirror set in its anti-glare position, the glare level could be greater than 1 lux under some conditions; disability glare effects could only be avoided by setting the exterior mirror to not reflect directly into the driver's eyes. The effects of glare persisted for 1 to 2 km after the following car was removed if the driver failed to use the anti-glare setting, but glare effects did not noticeably persist if the anti-glare setting was used.

The study also sought to relate levels of discomfort to levels of disability and to determine the amount of glare that motivated drivers to use the anti-glare position on their mirrors. Two levels of glare duration were used: 10 seconds and 3 minutes. Discomfort was rated using the 9-point scale discussed in Chapter 2. The conditions represented worst-case situations in that both mirrors were adjusted to reflect the illuminance from the following car into the driver's eyes in a normal driving position. The experiment was conducted on a dark, two-lane rural road with both young and older drivers. The results showed that discomfort was one scale unit more uncomfortable when drivers were exposed to glare for 3 minutes than when the exposure was only 10 seconds. Glare was rated slightly more disturbing than 5 (just admissible) when illuminance was as little as 6 lux for short durations and 3 lux for long durations; the Adler and Lunenfeld formulas show that these levels of glare approximate those from a low-beam system on a vehicle following at 30 m. Surprisingly, it was not until the level of discom-

[1] *For information contact Quantics at 3980 Del Mar Meadows, San Diego, CA 92130, or GLevy@Quantics.net.*

fort exceeded 3 (disturbing) that all drivers switched their mirrors to the anti-glare setting; at that level, disability glare would already have significantly degraded visibility. A subsequent study by Sivak et al. (1997), which sampled only drivers under age 43, showed similar results for the effects of glare duration, but the study also found large differences among the drivers.

Given that their studies showed the effects of disability, transient, and discomfort glare only under worst-case conditions, Olson and Sivak concluded that "if future lighting systems are made more powerful in an effort to improve night visibility, the problem [of mirror glare] will worsen." This is obviously what has occurred, as HID and high-performance halogen headlamps have led to more complaints from the public. Olson and Sivak suggested that, to encourage greater use of anti-glare mirrors, the reflectance of the anti-glare setting could be increased so that the setting could be used continuously. Alternately, they suggested lowering the reflectivity of the normal setting to provide some minimum protection against glare at all times. The automatic variable-reflectance mirror appears to satisfy this suggestion.

Misaim can greatly increase glare from rearview mirrors, as was reported by Miller et al. (1974), who found that reflected glare from the misaimed headlights of following vehicles exceeds the just-tolerable glare from oncoming headlights. Properly aimed low-beam headlights produced less mirror glare at intercar spacings as small as 50 ft than oncoming high-beam headlights at 600 ft, but misaimed low beams can exceed this glare level with intercar spacings as close as 150 ft. The study also found that glare increased by a greater amount when low beams were misaimed upward than when high beams were similarly misaimed. Low-beam headlamps misaimed upward by only one degree increased the illumination in the rearview mirror by a factor of 8 and produce more glare than encountered from oncoming high-beam headlights at 600 ft with intercar distances as great as 400 ft. To counteract the negative effects of a low beam misaim of only one degree, normal mirror reflectivity would have to be reduced to 10%, but even a mirror with less reflectivity than 10% might not counteract the combined effects of increased mounting heights, greater misaim, and higher intensity lamps.

A survey of 424 residents of Ann Arbor, Michigan (Flannagan and Sivak 1990) found that the most common way of using prism mirrors was to switch back and forth when bothered by glare. Twenty percent of the respondents said they never used the anti-glare setting and 16% left the mirror permanently in the anti-glare position. In terms of the severity of glare, oncoming headlights and inside rear-view mirrors received equal weight, whereas left outside mirrors were rated lower and right outside mirrors lower still. Both right outside mirrors and inside mirrors in anti-glare mode were rated close to the "no-problem" end of the rating scale. However, the effectiveness of prism mirrors is reduced by the substantial number of drivers failing to use them because they either forget or consider it too much trouble to switch back and forth. The results also indicated that, while there appears to be almost no problem with glare when the mirror is in the anti-glare mode, the anti-glare reflectivity level of only 4% may provide inadequate visibility to the rear.

These results suggest that there may be a tradeoff in controlling discomfort glare and maintaining rearward and forward visibility: Lower reflectivity reduces discomfort and increases forward visibility, but decreases rear visibility. There is conflicting evidence concerning whether improved rear visibility is actually needed. Drivers indicate that a major reason for not using the anti-glare setting is poor rear vision, but, unless the driver is backing up, the only important things to see in the rear-view mirror are overtaking vehicles (everything else is receding) and since all vehicles should have headlamps on them, they should be readily visible with a 4% reflective mirror. If the driver is backing up, he should not be relying on his rear-view mirror but instead should turn his head and look back. Flanagan and Sivak (1994) suggest some of the things that drivers may need or want to see to the rear, including empty pavement, road markings, and side panels of vehicles, but there is no evidence to support these suggestions. If what drivers want to see in the rear is the behavior of their children, safety might be better promoted with less, not more, rearward vision. If rear visibility is necessary either because drivers need to see or want to see more than the headlamps of overtaking vehicles, the alternative is the use of the more costly variable-reflectance mirrors.

A laboratory study by Flannagan, Sivak, and Gallatly (1991) evaluated rearward visibility (as measured by a visual acuity task), discomfort glare, and the driver's awareness of changes in ability to see rearward while using a variable electrochromic mirror. This study suggested that the tradeoff between forward visibility, rearward visibility, and discomfort might be found as a linear function of the logarithm of reflectivity. The continuous control of reflectivity allowed by electronic mirrors results in continuous perceptual changes that could allow some control of the tradeoffs required in night driving; for example, a gain in visibility can be achieved by accepting a corresponding loss in discomfort. It is interesting that the subjects in this study consistently underestimated their ability to see—drivers using these mirrors apparently do not believe that they see as well as they actually do. If this result is accurate, it might undermine the potential success of this product.

While the study suggested the possibility of optimizing the variable reflectivity of the mirror with respect to the tradeoff between discomfort glare and visibility, the research did not go so far as to develop an optimization algorithm. Toward this end, Flanagan and Sivak (1994) developed a computer model to evaluate the effects of mirror reflectivity in much the same way as Bhise et al. (1977, 1984) developed CHESS for evaluating the performance of low-beam headlighting patterns (see Chapter 5). The model produced a figure of merit that considered forward visibility, rear visibility, and discomfort glare. The figure of merit also reflected the percentage of night driving in which both visibility and discomfort criteria were met. As with CHESS, the results of the mirror reflectivity model depend on how the criterion levels for satisfactory performance are set, and also, as with CHESS, there is room for disagreement as to what drivers must see, particularly toward the rear. The new study did not offer any new optimization algorithms, but did suggest that the variable-reflectance mirrors in use today do a good job of satisfying the tradeoff between visibility and discomfort, and an even better job when used in both the center rear-view and left side positions.

There has not been any independent field research of either photochromic or neodymium mirrors in nighttime driving, so these technologies cannot be formally evaluated and their advantages and disadvantages cannot be assessed. While the concepts appear to be promising, controlled field testing is necessary to show how these devices work in various situations and, equally important, how drivers react to them.

Advantages

- If used, the prism anti-glare mirror should eliminate most problems from mirror glare, including glare from the high-mounted headlamps on SUVs and the brighter HID headlamps.

- Automatic variable-reflectance mirrors automatically regulate their use as a function of the presence of glare and eliminate the need for drivers to remember to use them.

Disadvantages

- The low level of retroreflectivity with the anti-glare position on prism mirrors results in poor rear visibility. Because of this, and the need to manually change the mirror position, these mirrors are not used by many drivers.

- Automatic variable-reflectance mirrors may result in drivers losing confidence in their visual performance and making inappropriate decisions while driving.

Advantages and Disadvantages of Photochromic Mirrors

While it is difficult to assess the advantages and disadvantages of a product not yet on the market, it is clear that the potential advantage of this technology is reduced glare without loss in rear visibility. Given the lack of consensus on the importance of rear visibility, the disadvantage is likely to be the tradeoff of whether or not the gain in rear visibility is worth the added cost.

Advantages and Disadvantages of Neodymium Mirrors

Neodymium mirrors are less costly than electrochromic and photochromic mirrors. The spectral effects of neodymium oxide in lighting and glass are well documented, but the practical effect of any change in the rendition of color must be tested with regard to the recognition of highway objects critical to safe driving. For rear-view mirrors such objects might only include flashing lights on maintenance vehicles and snowplows. Given the discovery by the Maryland Department of Transportation that a type of neodymium sunglasses completely blocked out yellow LED warning signs and traffic signals, it is clear that proper testing must be completed before this technology is accepted.

Summary

Anti-glare mirrors are an effective way to deal with most of the mirror glare from following or passing vehicles. However, their benefit is not fully realized because many drivers fail to use them or don't use them properly. Unfortunately, drivers do not recognize that their vision may be impaired by glare before they have any sensation of discomfort, and many drivers who do use anti-glare mirrors do not do so until experiencing a level of glare that results in disability. This behavior argues for the adoption of variable-reflectance mirror technology.

While the automatic variable-reflectance mirror is an effective solution to the problem of mirror glare, until these devices are available on all models in both the inside and left outside positions drivers should be encouraged to use their prismatic mirrors. In addition, drivers without a variable-reflectance mirror on the external driver's side should set this mirror so that the headlights of following vehicles do not reflect directly into their eyes. This is not an ideal solution, since much of the information otherwise provided by the exterior mirror is lost.

Since there is no conflict between maximization of forward visibility and glare reduction (both goals are achieved if the mirror is entirely removed), rear visibility is the sole reason for having a mirror. More attention should be given to determining the minimum reflectivity required; if this were known, the parameters of the variable-reflectance mirror could more easily be optimized.

Photochromic and neodymium mirrors are promising technologies requiring further research to demonstrate their function and safety as anti-glare devices. Cost appears to be the critical factor to the viability of the photochromic mirror, although there is also a need to demonstrate reliability and effectiveness. For the neodymium mirror, whose cost should be minimal, the critical factor is the effect of filtering yellow light on the visibility of emergency and maintenance vehicles.

The anti-glare mirrors described in this report may not be adequate to control the combined effects of greater illumination from HID and high-intensity halogen lamps, misaim, and the higher mounting heights of headlamps on SUVs. Additional research would help to define how anti-glare mirrors could control these variables, but it seems likely that the margin of safety that these devices provide would always be violated under certain circumstances. This limitation is particularly serious with following vehicles that create a glare situation for sustained periods of time. Therefore, while the combination of inside and left outside automatic variable-reflectance mirrors is a worthwhile addition to safer driving, other countermeasures, such as improved headlamp aiming and lower mounting height, still need to be pursued.

CHAPTER 7
COUNTERMEASURES THAT INCREASE THE GLARE ANGLE

- **Increased Median Width**
- **Independent Alignment**

MEDIAN WIDTH

The American Association of State Highway and Transportation Officials (AASHTO) defines the median as that portion of a divided highway separating the traveled way for traffic in opposing directions (AASHTO 1994). AASHTO also defines the principal functions of medians: "to separate opposing traffic, provide a recovery area for out-of-control vehicles, provide a stopping area in case of emergencies, allow space for speed changes and storage of left-turning and U-turning vehicles, minimize headlight glare, and provide width for future lanes" (AASHTO, 1994). Medians can be depressed, raised, or flush with the traveled way surface, and they should be highly visible during both day and night. The width of the median is defined as the distance between the through lane edges, including the left shoulders.

Soaring traffic volumes after World War II created a need for the immediate design of many highway facilities. In response to the urgent need, designers often relied on rules of thumb in their approach to median design, some of which have proven to be incorrect. According to Hutchinson et al. (1963), "these experiences have greatly stimulated research on median performance and factors of influence in median design." Among the "factors of influence" are benefits such as safety, comfort, and convenience. At the time of the report, the extent to which medians could provide these benefits was "more a matter of opinion than of record," and so it was difficult to use safety or comfort to justify any cost increases involved in varying the median width. This left the choice of basic median width an administrative decision, to be backed by engineering judgment.

Today, it is known that "reduced frequency of crossover accidents and [the] reduction of headlight glare are safety features associated with a wide median" (AASHTO 1994). Therefore, AASHTO recommends that, in general, a median should be "as wide as practical." Medians usually range from a minimum of 1.2 m to 24 m or more. The AASHTO report states that medians that are 12 m wide or wider provide the driver with a "desired ease and freedom of operation. . ." because there is a ". . . sense of physical and psychological separation from opposing traffic" (AASHTO 1994).

Increasing the median width decreases the effects of glare from opposing headlights by increasing lateral separation between vehicles. At any distance between vehicles on the road, increasing lateral separation will increase the angle between the driver's line of sight and the headlights of an opposing vehicle. In addition, increasing lateral separation effectively shifts the beam pattern of the opposing vehicle, resulting in lower intensities of light directed at oncoming drivers. The combined effect is a reduction of both disability and discomfort glare.

Figure 11 was prepared by Powers and Solomon (1965) to show the relationship between lateral separation, longitudinal (on-road) distance between vehicles, and veiling luminance. The calculations are based on the work of Fry (1954).

The figure shows that at any given longitudinal distance between an approaching car and a driver's eye, increasing the lateral separation will decrease the veiling luminance. As vehicles approach each other for a given lateral separation, the veiling luminance either uniformly decreases (for lateral separation of 32 ft or more) or first increases and then abruptly falls (for lateral separation less than 20 ft).

Research

Median Width vs. Headlight Glare

In a series of experiments, Powers and Solomon (1965) measured the effects of glare as a function of median width. Each of the three experiments simulated a meeting of a single vehicle and a single opposing glare vehicle on a constant-grade, tangent section of highway where both directions of travel were at the same elevation. The objective was to determine how changing the median width, and thus the glare experienced by the driver, would affect the detection of a target that was placed ahead of the subject's vehicle. The experiments differed with respect to the positioning of the subject vehicle, glare vehicle, and target. Table 5 summarizes the parameters of each experiment and the results that were found. Sample sizes were small (fewer than seven subjects in each study), and therefore, according to Powers and Solomon, the experiments do not give "super-reliant" data; nevertheless, they do give some insight. As expected, the effects of glare on target visibility decreased with increased lateral separation between the glare car and the opposing vehicle.

Median Width vs. Accident Rates

As mentioned above, the extent to which factors such as safety, comfort, and convenience are affected by median width is more a matter of opinion than of record. Early studies by Hurd (1957), Telford and Israel (1953), Crosby (1960), and Billion (1962) attempted to correlate accident rates to median width by studying accident records along different sections of roadways, but they were not able to establish a definite relationship between these two variables. It was apparent, however, that accidents where vehicles crossed the median and collided head-on with a vehicle traveling in the opposite direction were less frequent

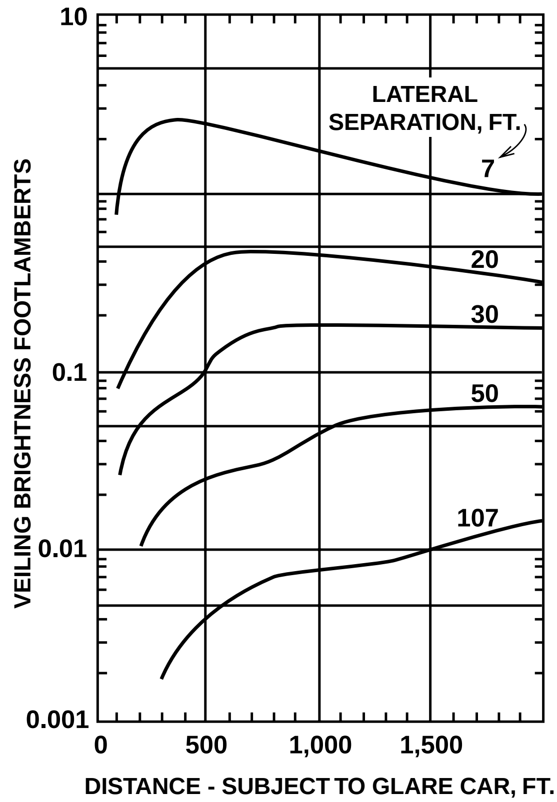

Figure 11. Veiling brightness vs. lateral separation (Powers and Solomon 1965).

where there were wider medians. As a result of this observation, the use of wider medians became commonplace (Garner and Deen 1973).

A problem with the early studies was that they did not recognize and control for several important variables that also affect accident rates, such as pavement width, shoulder width, grades, curves, sign locations, and access control on the roadway section. A subsequent study by Garner and Deen (1973) controlled for these variables and so obtained more conclusive results.

In the Garner and Deen study, 420 miles of rural, four-lane, fully controlled-access road sections with medians ranging from 20 ft to 60 ft were studied using an accident database that included 2,448 accidents recorded between 1965 and 1968. The results indeed showed that wider medians are safer medians. Figure 12 shows the accident rate found by the study as a function of median width.

Table 5. Summary of Studies by Powers and Solomon (1965)

	General Set-up of Experiment	Results
Study 1	The opposing glare car and the target were stationary; the subject drove toward the target and indicated when he could detect it. Subjects also indicated when they experienced discomfort glare.	The distance at which the target was detected increased with lateral separation and approached those of a no-glare condition at a lateral separation of approximately 80 ft. The distance from the opposing car at which the subjects reported discomfort glare generally increased as lateral separation was decreased.
Study 2	The target and the test subject were stationary and the glare car moved toward the subject. The subject reported at what point he could and could not see the target.	For some runs with small lateral separations, the target was not visible until after the glare car passed the subject car. For some larger lateral separations, the target was visible during the entire run.
Study 3	The target and the subject car were stationary and the glare car moved toward the subject. As the glare car approached the subject, the subject varied the brightness of the target so that it remained at the threshold of visibility.	At a given distance from the subject car to the glare car, the brightness necessary to maintain threshold visibility decreased as the lateral separation increased.

The Garner and Deen results were confirmed by Knuiman, Council, and Reinfurt (1993), in a study that examined the effect of median width on the frequency and severity of accidents in homogeneous highway sections. Data for this study were obtained from the Highway Safety Information System (HSIS) for the states of Utah and Illinois. A total of 3,055 miles of highway where there had been 93,250 accidents between 1987– 1990 was used for analysis. The median widths along roadways in the study ranged from zero (no median) to 110 ft. Overall, the study found that accident rates do decrease with increasing median width.

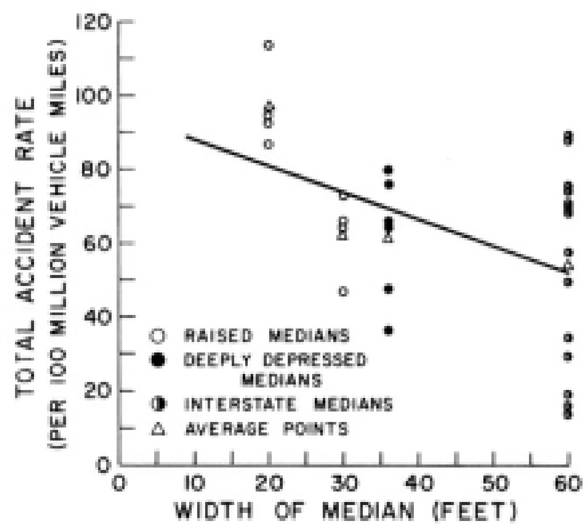

Figure 12. Total accident rate versus median width (Garner and Deen 1973).

Independent Alignment

Independently aligned roadways are those with horizontal and vertical alignments developed independently to suit location and design requirements (Peet and Neuzil, 1972). Independent alignment places each roadway at a different elevation, with a variable amount of separation between the different directions of travel, in contrast to a narrow-median design, where each roadway is at or near the same elevation and a constant distance apart. With independent alignment, the driver on one roadway might not even see an approaching vehicle on the other roadway—which, of course, eliminates glare entirely. Since independent alignment is used when there is a large median width, it provides all of the advantages of a wide median and more. Peet and Neuzil (1972) compared narrow median design with independent alignment and listed several advantages for independent alignment, which are shown below.

Advantages

In addition to decreasing the effects of both discomfort and disability glare, wide medians provide numerous other benefits that increase the return on investment:

Accident Reduction. Wide medians have the potential to decrease both the frequency and severity of accidents.

Safety Zone. Wide medians provide greater stopping or recovery abilities and space for vehicles that run off of the left edge of the pavement.

Driver Comfort. Psychological discomfort and stress from driving are greatly reduced when a wide median is available.

Visibility. Increasing the median width may also improve visibility. Less light from opposing headlights will fall on the pavement, thereby decreasing the background brightness for some objects on the road. This will increase the contrast between pedestrians and other objects which are seen in positive contrast (that is, object brighter than pavement).

Additional advantages of independent alignment over narrow-median designs include:

Less earthwork required. Independent alignment permits the designer to avoid areas of difficult topographic, soil or drainage conditions.

More Environmentally Friendly. With independent alignment there is less likelihood of slope failures and erosion, groundwater problems, and bedrock excavation. Also, the highway may be located and designed in a manner that produces a minimum of visual and environmental disruption.

Disadvantages

There are few disadvantages associated with wide medians. The major disadvantages are the additional cost involved.

Increased costs. Wider medians increase construction costs due to the following factors: (1) extra right-of-way must be purchased; (2) additional gratings, seeding, mulching, and earthwork would be required; and (3) more maintenance (mowing and shrubbery) would be required.

Poor traffic signal operation. A less-apparent disadvantage of wide medians is found when at-grade intersections are required: The increased time needed for vehicles to cross the wide median may lead to inefficient traffic signal operation.

The disadvantages of independent alignment are:

Increased construction time. There are more nonproductive equipment movements required during the construction of independently aligned roadways than with narrow-median roadways.

Right-of-way Requirement. Independent alignment requires a larger amount of right-of-way than narrow median designs.

Summary

Wide medians and independent alignment are effective means of controlling glare from oncoming vehicles and can often be justified by accident reduction alone. However, this countermeasure is not a practical solution to the glare problem on many roads, particularly two-lane rural roads, where the traffic volume is low, and urban arterial roads, where land is not available to increase the right-of-way. As stated earlier in this report, glare from oncoming vehicles is primarily a problem on two-lane roads, and many of these will continue to be such for some time. An additional solution to glare is needed for these situations.

CHAPTER 8
COUNTERMEASURES THAT INDIRECTLY MINIMIZE THE EFFECTS OF GLARE

- **Ultraviolet Headlights**
- **Fixed Roadway Lighting**
- **Restricted Night Driving**
- **Corrective Lenses and Ophthalmic Surgery**
- **Headlamp Area**

Ultraviolet Headlights

Ultraviolet (UV) headlighting has the potential to reduce glare on the highway by reducing the need for visible light. Although not itself visible, UV radiation (UVR) can improve nighttime visibility of pedestrians, lane lines, signs, and other objects on the road. Either replacing high-beam headlamps with UV headlamps or modifying the low-beam photometrics in a UV-enhanced lamp (perhaps using a European beam pattern) could eliminate much of the glare experienced by drivers of oncoming vehicles and still maintain visibility. Even without any reduction in glare from visible light, disability glare effects may be reduced by the improved visibility.

Ultraviolet radiation cannot be seen by most human observers, but, when it is absorbed by certain materials, UV is converted to longer-wavelength visible light. This phenomenon, called fluorescence, makes objects more easily seen and is the reason that UV headlamps have the potential to improve highway safety. Unlike standard automobile headlamps, UV headlamps' intensity and alignment can be adjusted to optimize visibility without concern for glare.

UVR ranges from approximately 4 nm to 400 nm wavelength, but UV headlamps operate in the relatively long-wavelength UVA band, which ranges from 320 nm to 400 nm. The cornea and aqueous humor of the human eye absorb all UVR below 300 nm (Kinsey 1948) and approximately 50% up to 365 nm (Zigman 1983); the healthy adult lens absorbs nearly all of the remaining UVR (Ham, Mueller, Ruffolo, and Guerry 1980, Zigman 1983). However, two groups of individuals do experience significant transmission of UVA and perceive it as light: youths under the age of ten (Lerman 1983) and the elderly who have undergone eye surgery to remove and/or replace a lens (Anderson 1983, Sliney et al. 1994, Wald 1945, Zigman 1983).

Research

Most of the research on using UVA headlamps for enhancing highway visibility has been conducted in Europe, in particular by the Swedish National Road Administration. In the U.S., the Federal Highway Administration (FHWA) became active in the mid-1990s, sponsoring a study entitled "Safety Evaluation of Ultraviolet (UVA)-Activated Fluorescent Roadway Delineation" (Nitzburg et al. 1998). This study included a comprehensive literature review, which, together with documentation of the study, can be obtained on the Internet. More recently, the FHWA has funded a consortium to undertake a comprehensive look at all aspects of implementing this technology.

Visibility — In general, the Swedish research has shown that UV headlighting significantly improves the visibility of anything on the highway that contains fluorescent pigments, without any increase in glare. While UV light alone did not enable drivers to see where they were going, it did increase the visibility distance to objects such as lane lines and pedestrians. UV headlights were able to highlight anything that contained fluorescent pigments, including road signs, road markings, and clothing. Pedestrians were seen more clearly and at further distances and the path of the roadway could be seen far beyond oncoming vehicles, thanks to the fluorescent road markings that were used. While UV light may highlight the fluorescent pigments in some road signs, there is not likely to be a noticeable effect from visible light, as fluorescent materials are much less effective in producing luminance than retroreflective materials.

Clothes vary in their degree of fluorescence, depending on material and color. Studies have found that even fabrics of relatively low fluorescent efficiency, such as jeans, could be seen at approximately 100 m (328 ft) in the presence of glare and at more than 150 m (492 ft) without glare; in the absence of UV headlighting, the low-beam visibility distances were 60 m and 70 m (197 ft to 230 ft). The improvement in visibility was even greater for white cotton clothes and synthetic fabrics, but dark clothes, such as black wool, were no more visible with UV light than with normal low beams. Washing can improve the fluorescent properties of garments because many detergents contain optical whiteners, which convert ultraviolet light into visible light.

A report from Ultralux (1994), cited in Nitzburg et al. (1998), states that fluorescent road markings can be seen at a distance of 150 m (492 ft) with UVA light, compared with 60 m to 70 m (197 ft to 230 ft) with ordinary low beams. The improvement in visibility distance for roadside posts was even better: they could be seen at more than 200 m (656 ft) with UVA light.

Helmers et al. (1993), in a study cited by Nitzburg et al. (1998), evaluated detection distances for black, gray, and white targets as well as for clothing under low-beam illumination supplemented by UVA. The study was a full-scale simulation of two opposing vehicles on a straight, level, two-lane road closed to traffic. The additional UVA illumination resulted in only a slight increase in detection distance for the black and light gray targets but caused a doubling in detection distance for the white targets. The ability of clothing to emit visible light in response to UVA lighting was found to depend on reflectance: When the reflectance of the clothes increased, the visible light resulting from UVA increased much more rapidly than the reflected ordinary light.

Nitzburg et al. (1998) found similar improvements in visibility from UVA in a series of tests that included static tests to determine detection and recognition distances for pedestrians, bicycles, disabled vehicles, traffic cones, and delineation, and dynamic tests to measure driving speed and lateral lane position, as well as subjective comparisons of different headlighting configurations. The study found that using UVA in addition to conventional U.S. low-beam headlights increased recognition distance by between 14% (right curve) and nearly 50% (no-passing zone and crosswalk). Still greater improvements were observed in the presence of oncoming headlight glare, suggesting that UV could be a direct countermeasure for disability glare. Objects that have fluorescent but no retroreflective components (cones and bicycles) experienced improvements in detection and recognition distance of greater than 250%, whereas objects that have only retroreflective components (disabled vehicle) showed no significant improvement in visibility. Detection distances for five different pedestrian cut-outs (child, adult, tall adult, kneeling adult, and jogger) ranged from 60–250 m with UVA, representing increases of 20–140 m over conventional headlighting.

When asked what headlights they liked best and what headlights enabled them to best steer the car, drivers clearly favored the U.S. low beam and UVA combination. Still, performance comparisons in speed and lateral lane position showed no significant differences between the headlighting systems that were tested, with or without UVA.

The studies indicated one potential danger of UVA headlighting: Some of the fluorescent objects were so highly visible that they may have distracted drivers from attending to other objects. This is one of many human-factor issues that will need to be addressed before UVA can be accepted as a headlighting alternative.

The FHWA is currently sponsoring a comprehensive research and development program to support a universal UVA headlighting system. The program, which is being carried out by the Virginia Institute of Technology Center for Transportation Research and the University of Iowa, is intended to do the following:

- Develop a UVA headlamp specification
- Evaluate fluorescent infrastructure materials
- Quantify the glare and photo-biological risks
- Perform a cost/benefit analysis
- Conduct a demonstration and implementation of the system

Without headlamp specifications (including the photometric pattern for both visible light and UVA), the effectiveness of UVA as a countermeasure will remain unknown. The project will consider coupling UVA with current low-beam, improved halogen, HID, and European headlamps in an effort to determine the ideal combination for advancing this technology. Although HID lamps produce a considerable amount of UV radiation, very little of this is UVA and most UVB and UVC is filtered for safety reasons (Schoon and Schreuder 1993). To use UVA with HID would probably necessitate separate light sources.

To some extent, the optimum beam patterns cannot be identified until there is an assessment of the fluorescent infrastructure materials. It is still unknown, for example, whether the beam pattern should be designed to emphasize the visibility of road delineation, hazards, or pedestrians. Many additional questions need to be addressed. The viability of the concept depends on the assessment of risk and a realistic assessment of costs and benefits, and so these issues are also being addressed. Only after an effective system is defined and understood can the process of marketing the idea to the public and industry begin.

Health - The basic premise that UV is imperceptible to human observers is not quite true; some people actually do see near-UV radiation as light. Infants and children are one such group. During the first year of life, more than 80% of radiation in the UVA range is transmitted through the lens of the eye, and less than 25% of UVA radiation is absorbed by the lens by age ten. It is not until 25 years of age that lenticular UVA absorption reaches its highest level—about 80% (Lerman 1983).

The 1990 U.S. census recorded over 37 million children under the age of ten. These youths will be substantially more sensitive to radiation from UV headlamps than normal adult observers. When detecting a young pedestrian or bicyclist, courteous motorists turn off their standard high beams to reduce glare for these individuals. If the driving population is led to believe that UV headlamps are invisible to the human eye, they will not be sensitive to any discomfort and disability they may inflict. The extent of the glare effect is emphasized by Sliney (1994), who stated that “any young child, aphakic or pseudophakic person [no lens or artificial lens] whose retina is exposed to a significant level of UVA will have a strong aversion response....” (Sliney et al. 1984, p. 15).

Intraocular lens implantation (IOL). Both the normal aging process and constant exposure to natural UVA radiation lead to an increase in lenticular fluorogens (UV-absorbing chromophores) and to opacification (lens yellowing) so that eventually the lens absorbs nearly all UV radiation in the 300 to 400 nm range (Lerman 1983). It is thought that, as an individual ages, this constant absorption of UV radiation plays a significant role in the formation of cataracts (Zigman 1983). Currently, the surgical treatment of choice for cataracts is lens removal and implantation of an artificial lens. If the artificial lens is not treated with UV-absorbing monomers and polymers—and many older implants were not—then all of the UVA that is transmitted through the cornea and aqueous humor will reach the retina (Pitts 1990) and be perceived as visible light (Anderson 1983, Wald 1945).

Ultraviolet-absorbing IOLs. If an IOL is not specifically treated to absorb UVR, the retina of the wearer will be exposed to radiation in the UVA range (Werner and Hardenbergh 1983, Zigman 1983). Research studies report that aphakic individuals and pseudophakic individuals without UV-absorbing IOLs have 47 times the sensitivity of normal individuals to UVR at 380 nm (Werner and Hardenbergh 1983) and 1000 times the normal sensitivity at 365 nm (Anderson 1983). Furthermore, some lenses that purport to be UV-absorbing have been found to transmit up to 70% of UVA radiation (Pitts 1990).

In 1983, the first UV-absorbing IOLs were designed (Zigman 1983). While it is impossible to say exactly how many IOLs are in use today, it was not until 1985 that a substantial proportion (48%) of lens implants used this design (Stark et al. 1986). The government still does not require UVR absorption treatments in IOLs (USHHS 2001).

Chromatic Aberration: Like most optical systems, the human eye focuses different wavelengths of light at different spatial locations; in a phenomenon called chromatic aberration. If the eye is focused on a yellow object, blue objects will focus in front of the retina, and red will focus behind the retina. An example of chromatic aberration is the depth effect that occurs when a highly saturated blue and a highly saturated red are juxtaposed. Chromatic aberration is not a noticeable problem unless the eye attempts to focus simultaneously on two divergent wavelengths. Unfortunately, this is just what will happen when individuals with UV-transmitting lens implants try to see objects illuminated by UV headlamps.

Artificial IOLs are designed to focus light optimally in the spectral range of highest daytime retinal sensitivity, which is centered around 555 nm wavelength. If external objects are illuminated predominantly by light of wavelength 320–400 nm, a blurring effect will occur. Although younger UV-sensitive individuals can compensate for the UVA underfocus by accommodation, the artificial lens exacerbates chromatic aberration and removes the eye’s ability to control focal length.

Two studies investigated the effects of chromatic aberration in the presence of UVA illumination: one in which monochromatic monitors were used to test contrast sensitivity (Hammer, Yap, and Weatherill 1986) and another where wall charts were used to test visual acuity (Rog, White, and Williams 1986). The former study found visual performance to be unaffected by IOL absorption of UV; individuals with UV-transmitting lens implants performed as well as those with UV-absorbing lenses. The latter study found a significant reduction in acuity for individuals fitted with UV-transmitting lenses when the test charts were bathed in light containing a UVA component; optotype visual acuity was reduced from 20/46 to 20/57 and vernier acuity was reduced from 20/65 to 20/78.

The observed reduction in visual acuity in the presence of UVA could directly affect a pedestrian's ability to read signs, and the perceived color of traffic signs will likely change for these individuals (White and Wolbarsht 1975). Furthermore, if light from UV headlamps is transmitted through automobile rear and side windows, a UV-sensitive driver's ability to read in-vehicle instrumentation could be compromised. UV-sensitive individuals may not be aware of the loss in visual function and so might engage in risky behavior.

Aside from the possible drawback of adverse effects on UV-sensitive individuals, the benefits of a UV headlamp system could be considerable. A vehicle equipped with UV headlamps could be operated with the lamps on continuously, conceivably increasing pedestrian detection by 50 m to 100 m over standard low-beam headlamps (Fast and Ricksand 1984). Replacing current high beams with UV headlamps would dramatically reduce glare to oncoming vehicles and increase visibility by not forcing drivers to dim their lights for oncoming traffic. Furthermore, because UV headlamps do not cause glare, they could be aimed solely to optimize visibility.

Further study is necessary to determine whether the effects of UVA headlighting on UV-sensitive individuals would result in real safety hazards or merely increased discomfort for a subpopulation.

The literature supports the idea that UV-sensitive individuals will experience reduced visibility due to glare or chromatic aberration resulting from UV headlamps. This reduced visibility could cause a safety hazard for both pedestrians and drivers. Future research should study glare, acuity, and contrast sensitivity using illuminants that match the spectral output of UV headlamps at the intensities expected under normal roadway conditions.

Other health risks - The dangers and problems of ultraviolet light have been investigated by the Swedish Road and Traffic Research Institute and are currently under investigation in the FHWA study mentioned earlier. One proposal to remediate the problems is to use filters to remove most of the harmful rays. Filtering the lower UV wavelengths reduces biohazards (which includes premature aging of the skin and skin cancer) and filtering the upper end (near the visible range) limits the potential to generate glare. With such filters, the UV lamps appear black in daylight and glow faintly blue in the dark. In addition to the use of filters, the Swedish Road and Traffic Research Institute has proposed that sensors be used to turn off the UVA component when speed is reduced below 48 km/h (30 mph). This practice, which is also under consideration by the FHWA, is intended to minimize the health threat to pedestrians.

Materials - Widespread implementation of UVA headlighting will require the development of new traffic control devices. Kozak (1996), cited in Nitzburg et al. (1998), identified materials that were likely to produce stable, long-life traffic control devices and identified specific problems that must be addressed before any implementation is undertaken. The FHWA study in progress will evaluate alternative lighting systems in connection with fluorescent pavement markings, pedestrians, cyclists, and workers with fluorescent vests. This evaluation could be hampered by poor availability of materials; for example, not all colors are available in fluorescent material. Measuring an object's luminance under UVA relative to its irradiance gives an indication of the fluorescent efficiency of its components. Fluorescent efficiency will vary with the spectral composition of the UVA source, and so is dependent on the actual filters chosen for the system. The largest obstacle to the development of new materials is that industry has little incentive to develop them without the implementation of UVA headlighting, but UVA headlighting cannot flourish without the required materials.

Advantages

- UVA offers the potential to offset the negative effects of disability glare by improving the visibility of objects in the presence of glare.

- Improvements in visibility raise the possibility that high beams could be eliminated and the sharp-cutoff low beam pattern used in Europe might become acceptable.

- The greatest improvement in visibility is expected in places without street lighting, which are currently the places with the greatest problems from glare.

- Since UV light is not normally visible, its backscatter under adverse weather conditions is not visible either. Therefore, glare from backscatter could potentially be reduced and visibility improved in such conditions.

Disadvantages

- The potential health threat to children and the elderly needs to be quantified and the corresponding liability issues must be addressed.

- Longer UVA wavelengths might produce glare. Filters to eliminate such glare may reduce UVA output, reducing its efficiency with respect to power consumption.

- The introduction of UV headlamps does not eliminate the need for low-beam headlamps, because visible light is still required to illuminate retroreflective signs; this visible light will continue to cause a glare problem.

- Perhaps the biggest threat to the viability of UVA headlighting is the limited durability of fluorescent traffic control devices. There is some evidence that suggests that the life cycle of these products is limited. If they require frequent replacement, costs will increase and cost-benefit ratios will be less favorable. Less obvious is the threat that this problem poses to realizing any benefits at all. If fluorescent devices are not maintained, then not only would the benefits of accident reduction be lost, but the accident rate may very well be higher than before the introduction of UVA. This problem would be still worse if glare countermeasures such as elimination of the high beam and modification of the low beam are implemented.

- The apparent improvement in visibility might lead to higher speed and more risk-taking.

- The above-threshold levels of visibility that can be achieved with UVA may prove distracting and result in some critical targets going unnoticed. Whether drivers will adapt and eventually ignore these distractions is not known.

- The costs of implementing this technology are still uncertain.

Summary

Given the extent and magnitude of the research needed before UVA could be implemented at the national level, it is impossible to assess the viability of this technology. Clearly, UVA has the potential for developing headlight systems that attain the longstanding goal of improved visibility without added glare. It is unlikely that UVA can reduce the level of glare generated by low beam headlamps, because UV headlamps would not eliminate the need for low-beam headlamps—visible light would still be required to illuminate retroreflective signs, since fluorescent materials are much less effective in producing luminance than retroreflective materials. Clearly UVA has many problems, including health issues and the availability, durability, and cost of materials.

Fixed Roadway Lighting

In the U.S., fixed roadway lighting is generally designed according to one of the three methods described in the American National Standard Practice for Roadway Lighting (RP-8 2000), each based on illuminance, pavement luminance, or visibility. Fixed roadway lighting is installed for many reasons, including reduction in nighttime accidents (primarily on major arterial roads and freeways), pedestrian safety, crime reduction, and area ambience (on urban streets and areas with significant retail activity at night). In addition to these specific purposes, a secondary benefit of fixed roadway lighting is the mitigation of the effects of headlight glare.

During daylight, headlight glare is generally not a problem because of high visual adaptation in bright ambient light. At night, a driver's adaptation level is much lower and headlight glare becomes a problem. Adaptation level is determined by the entire visual environment, which can include the surrounding ambient lighting in visually complex areas, the steady stream of oncoming headlights, or the luminance of the pavement in areas without much traffic or ambient lighting. Fixed roadway lighting is a countermeasure against headlight glare whenever pavement luminance is a significant factor in determining the driver's adaptation level.

Research

The theoretical concepts used in evaluating fixed lighting and pavement luminance as a countermeasure for glare were discussed in Chapter 2. Pavement luminance has a direct effect on both discomfort and disability glare. As shown in equation 5, discomfort glare is determined partly by adaptation luminance, and insofar as pavement luminance determines adaptation, it also affects discomfort glare. With regard to disability glare, it was suggested in Chapter 2 that veiling luminance be limited to below 15% of background luminance (generally dominated by the pavement luminance) in order to minimize the effects of glare.

Each of the three design methods in RP-8 attempts to maintain minimum pavement luminance levels. The illuminance method (RP-8, Table 2) does this by requiring greater illumination on those roads with less reflective pavements and less illumination on more-reflective pavements such as concrete. The luminance method establishes minimum levels of pavement luminance for different types of roads (RP-8, Table 3). The visibility method (RP-8 Table 4), in addition to having minimum visibility levels for a standardized target, also sets minimum pavement luminance levels to control disability glare from an oncoming vehicle 85 m away, both with and without a median separator. The resulting pavement luminance requirements for the visibility method are somewhat lower than those for the luminance method, but they are still thought sufficient to control disability glare whenever pavement luminance is prominent in establishing driver adaptation.

The effectiveness of fixed lighting systems in reducing night accidents has been evaluated by using daytime accidents as the basis of comparison between sites with different lighting systems and by comparing the accident rate at a given a site before and after a change in lighting. These studies have invariably indicated that the night accident rate is reduced when supplementary fixed lighting systems are installed. According to RP-8:

> The nighttime fatal accident rate is about three times the daytime rate based on proportional vehicular kilometers/miles of travel. This ratio can be reduced when proper fixed lighting is installed because these lighting systems reveal the environment beyond the range of the vehicle headlights and ameliorate glare from oncoming vehicles by increasing the eye's adaptation level...the IESNA Roadway Lighting Committee is of the opinion that the lighting of streets and highways generally is economically practical. These preventive measures can cost a community less than the accidents caused by inadequate visibility.

Cost-benefit analysis of lighting on the basis of accidents is not possible since the research is inconclusive concerning how much light is necessary for maximum accident reduction. Several studies from the 1970s indicated that safety benefits are not always seen after additional investment in lighting. In his analysis of 22 freeway sites, Box (1973) found that, although lighted freeways had a lower ratio of night to day accidents than unlighted freeways, 11 sites with horizontal illumination greater than 6.4 lux had a higher night/day accident ratio than sites with illumination of less than 5.4 lux. A graph of night/day accident rates as a function of illumination level had a U shape with high ratios both for low and high levels of illumination. Box concluded that the best night/day accident ratios were found on lighted freeways with illumination of about 6.0 lux. While other studies have supported this conclusion, the relationship between the amount and quality of lighting has not been well established.

According to the National Safety Council (1999) the nighttime traffic death rate in 1998 was 4.4 times the day rate. Of the 18,874 nighttime traffic fatalities in 1998, over 56% took place on rural roads. Surprisingly, although vehicle mileage is less on rural than on urban roads and even less at night, the nighttime rural death rate for the past decade has consistently been three times the rural day rate and 2.5 times the urban nighttime death rate. According to Keck, Wortman concluded that fixed lighting was warranted on a cost-benefit basis whenever the night-day ratio exceeds 3.0. Using this standard, there are likely to be many rural locations that would benefit from lighting; once in place, the lighting would also help mitigate the effects of glare.

Advantages

The benefits of fixed roadway lighting as a countermeasure for headlight glare are twofold. First, fixed lighting increases the visibility of objects and pedestrians on the road, making it possible to reduce the headlight illumination required. Second, fixed roadway lighting raises the adaptation level of the driver, thus reducing the effects of headlight glare.

Improved visibility with less headlamp illumination. Given that motorists use high beams infrequently in meeting situations, if at all (Hare and Hemion 1968), there is little to be gained from fixed lighting in terms of reducing high beam usage. If fixed lighting were to result in a reduction of headlight illumination it would be due to the use of adaptive headlighting or the elimination of low-beam headlamps in some situations. For example, some European cities once encouraged motorists to switch to parking lights within the city limits, where fixed overhead lighting is prevalent and good. While this practice has been largely discontinued because of the difficulty it created for pedestrians to see an approaching vehicle in advance, daytime running lights might prove to be an adequate substitute. In either case, implementing such a policy in the U.S. would require significant improvements in the fixed-lighting infrastructure and a clear definition of what constitutes good lighting.

Reduction of discomfort glare. Adequate pavement luminance from fixed lighting would mitigate the effects of headlight glare in environments that are otherwise relatively dark and where there is not a constant stream of traffic.

Reduction in nighttime accidents. Numerous studies show that fixed lighting lowers the nighttime accident rate. With nighttime accident rates often four times the daytime rate, fixed lighting systems can pay for themselves in accident reduction alone.

Disadvantages

Fixed roadway lighting has only two disadvantages: cost and hazards from the poles supporting the luminaires, which become a significant factor in fixed-object accidents.

Increased costs. Lighting systems involve fixed costs for poles and luminaires and maintenance costs for lamp replacement and electricity. High maintenance costs have led some agencies to move toward high-mast lighting, which allows lamp replacement without the use of a bucket truck and disruption of traffic.

Effect on accidents. Thirty years ago, there were estimates that lighting poles were involved in 5% to 35% of fixed-object accidents (Farber et al 1971, Cassel and Medville 1969). This problem has been recently addressed by requiring greater pole setbacks and by the use of breakaway poles; as a result, the role of poles in accidents has likely been reduced.

Summary

Fixed lighting appears to be an effective countermeasure to the negative effects of headlamp glare that also improves visibility and reduces accidents. Rural two-lane roads would apparently benefit most from fixed lighting, because in these areas pavement luminance is more likely to determine visual adaptation than any other source of light, glare from oncoming headlamps is at its worst, and the night-day accident ratio is highest.

Restricted Night Driving

Throughout this report, countermeasures aimed at reducing or eliminating glare have been inventoried and evaluated. These remedies have dealt mainly with changing the glare source (for example, by intensity reduction or wavelength modification) or altering the conditions through which the light passes (such as those in windshields and ocular media). However, there is no glare problem that does not involve the performance loss or increased discomfort of a human operator. Discomfort and disability glare are not the inherent characteristics of a light source, but rather are the result of an interaction between light source, environment, and observer—and with regard to glare sensitivity, not all observers are created equal. Therefore, one countermeasure which would alleviate at least part of the glare problem is to enforce or encourage night driving restrictions on those most sensitive to glare. This could be done through law or by means of self-imposed behavioral changes, as advocated by driving improvement programs aimed at older adults.

Research

Research on individual differences in and age-related changes to glare sensitivity and to glare recovery time have been treated elsewhere in this report. The effectiveness of restricting night driving as a glare countermeasure, however, hinges on the availability of an accepted measure of glare sensitivity and the establishment of a causal relationship between glare sensitivity and traffic safety. The literature on these two topics is not encouraging. The reviews of vision screening by Bailey and Sheedy (1988) and Hu, Lu, and Young (1993) found no standardized, clinically acceptable measure of glare sensitivity. Hu et al. (1993) added that, although glare tolerance is important, there is no statistical link between highway accidents and glare recovery. Shinar (1977) similarly found that glare tolerance and recovery time had little relationship with driving safety.

Even in the absence of hard scientific data, however, some researchers have made the judgement call that persons with glare problems should restrict their night driving. For example, Hu et al. (1993) stated that, "Individuals with problems adjusting to glare should limit their driving to daylight hours," and Bailey and Sheedy (1988) wrote, "Individuals who are known to perform poorly on tests of glare or night vision should be considered for night driving restrictions." Staplin (1994) noted, "Older drivers' self-awareness of declining vision, together with the high face validity of vision testing to safe driving performance, makes license restriction on this basis socially acceptable...." This insight reduces the urgency for associating glare with traffic safety, but still leaves unresolved the issue of identifying an appropriate screening device.

Most driver refresher courses encourage older drivers to avoid night driving and warn that conditions such as cataracts and glaucoma magnify problems with headlight glare.

Advantages

To the extent that disability and discomfort glare negatively impact both traffic flow and safety, the benefit of restricting night driving for those most effected by glare would be to improve these two critical transportation indices. However, the advantages may extend beyond the control of glare. Those whose licenses would be restricted or who would limit their own night driving on the basis of glare sensitivity are likely to be those whose nighttime visibility requirements were not adequately met in other areas of performance, because increased glare sensitivity is closely correlated with other visual deficits (Schieber 1988). The advantages might therefore also include an overall reduction in visibility-related nighttime crashes. Furthermore, if older drivers would be the most likely to have restricted licenses or to restrict their own driving on the basis of glare, then the reduction in crashes could result in an overall decrease in fatalities and injury severity, because older drivers are disproportionally represented in these two areas.

Disadvantages

The principal disadvantage of restricting night driving is the loss of nighttime mobility of the restricted drivers, most of whom would be older individuals who are already experiencing reduced mobility. Without community planning and involvement (including such measures as shuttle bus transportation), the costs associated with any reduction in mobility would be distributed among family and friends, who would be required to transport those who chose to avoid night driving.

An argument against license restriction is the cost of adding another component to driver's license screening. The actual costs associated with adding glare screening to driver licensure is not known, in part because no mechanism is now available, but Bailey and Sheedy (1988) list the following cost-related issues that must be considered:

- Record keeping
- Equipment costs and maintenance
- Staffing
- Staff training
- Overhead (room costs and so on)
- Applicant time

If there is a safety benefit, however, these costs could be offset by a reduction in the costs of glare-related crashes.

Summary

While license restriction appears to have the potential to reduce some of the reported problems with glare, more research is required before it can be recommended. A cost-benefit tradeoff is complicated, for a number of reasons:

1. The cost of administering the screening is unknown.
2. The social and personal costs associated with the loss of nighttime mobility may be incalcuable.
3. The benefits of reducing the number of glar-sensitive drivers on the road at night are unknown.

Before the costs and benefits of license restriction can be identified, standardized, clinically acceptable instrumentation must be available for measuring glare sensitivity, and a sound, empirically-based criterion for glare sensitivity must be determined.

Without a sound cost-benefit argument, a license restriction based on glare sensitivity would be politically unpopular and indefensible. Self-imposed restrictions on night driving such as those encouraged by driver refresher courses might be the most reasonable method to restrict the night driving of those bothered the most by headlight glare. Family members and family physicians can also play a role in encouraging older drivers to limit night driving.

Corrective Lenses and Ophthalmic Surgery

In a vacuum there is no glare. The perception of glare is the result of aberrant light transmission through some medium. Light emanating from headlamps must pass through air, windshield, any corrective lenses the driver is wearing, and various optical media (including cornea, aqueous humor, lens, and vitreous humor) before reaching the retina. Any changes in refractive index from one medium to the next will cause light to change direction (refraction), and any small particles in the medium will cause light to scatter (glare). The effects on glare of atmospheric conditions, windshield treatment, and optical media are mentioned elsewhere in this report. This section will be devoted to a treatment of glare effects when light passes through corrective lenses (eyeglasses and contact lenses), corneal modifications made during surgical procedures to correct refractive error, and artificial intraocular lenses implanted during cataract surgery.

Research

Corrective Lenses

The departments of motor vehicles (DMVs) in all states require that myopic (nearsighted) drivers of any age wear corrective lenses if their visual acuity falls below a set criterion (such as 20/40). (Despite this requirement, USA Today in September, 1999 reported that 10 states do not require vision testing for license renewal.) Many older drivers have presbyopia, and although they can see distant objects clearly they must wear corrective lenses to read in-vehicle displays. In the late 1980s, the Iowa Department of Transportation estimated that as many as 75% of drivers over 75 years of age were wearing corrective lenses (Iowa DOT 1989).

It has been proposed that scratched or dirty eyeglasses and contact lenses might exacerbate the effects of glare by scattering incoming light. For example, Schieber (1988) stated that glare can result from damaged contact lenses or, as found by Miller and Lazenby (1977), from corneal injury due to prolonged contact lens usage. However, there has been very little research conducted on this topic.

An exhaustive keyword search of the Transportation Research Information Services (TRIS) database, which contains over 400,000 records, together with queries of professionals in the field resulted in the discovery of only one research study that directly evaluated the impact of corrective lenses on glare. In that study, Sivak, Flannagan, Traube, and Kojima (1997) asked a group of myopic subjects to compare discomfort glare with contact lenses to that with eyeglasses; subjects reported no difference between the two. The study also found no significant difference in discomfort glare between subjects who wore corrective lenses and those who did not. This single study, involving only sixteen subjects, certainly does not provide a definitive answer to whether corrective lenses affect glare, and it does not contradict Scheiber's (1988) statement that damaged lenses may cause disability glare. Study subjects could well have had corrective lenses that were clean and free of scratches, and in any event this laboratory study may not directly apply to the nighttime highway environment. However, in the absence of any conclusive empirical data on the effects of corrective lenses on glare, it would be prudent for drivers to keep their glasses and contact lenses, like their windshields, clean and free of scratches and abrasions.

Ophthalmic Surgery

Refractive Error — Radial keratotomy (RK), photorefractive keratectomy (PRK), and LASIK (laser in situ keratomileusis) are surgical procedures to correct refractive error. In RK surgery, a blade is used to make radial incisions in the cornea, whereas in the other techniques, the front portion of the cornea is removed (PRK) or pulled back (LASIK), and a layer of stroma, or corneal tissue, is shaved off with lasers. All three techniques involve reshaping the cornea in an effort to change its refractive index so that light is better focused on the retina.

Most recipients of these procedures have reported increased sensitivity to glare and have experienced "flaring" (streaks of light emanating radially from a light source), and/or "haloing" (the appearance of an annulus of light around a light source) from oncoming headlights, at least in the initial three to six post-operative months (Consumer Reports 1999). This increased glare sensitivity occurs when the pupil dilates at night to a size larger than the portion of the cornea that was modified by surgery. Currently, refractive surgery in the U.S. occurs within a 6 mm zone. Light passing through the edge of the zone will scatter. If pupil size is larger than 6 mm—a common occurrence for young people at night—there will be glare. This is a permanent condition, though it may become less prominent after the first six months following surgery when the edge becomes smoother. Because of this phenomenon, measurement of patient maximum pupil size is recommended as a precursor to this type of surgical procedure (Applegate and Gansel 1990, Applegate 1991).

Pupil size, however is not the only contributing factor to glare. Glare may also be the result of slight irregularities (optical aberrations) in the modified area of the cornea. Proponents of refractive surgery assert that most, if not all, glare effects dissipate within the first six months of surgery, but a recent Consumer Reports (1999) article stated that perhaps as many as 10% of patients have lasting problems with "glare, ghosting, or fuzziness." Other studies reported in the medical literature have found reduced contrast sensitivity, poorer low-contrast visual acuity, and glare disability for up to two years after surgery (Applegate, Hilmantel, and Howland 1996, Applegate, Trick, Meade, and Hartstein 1987, Ghaith, Stulting, Thompson, and Lynn 1998).

Cataracts — It is hypothesized that, as an individual ages, absorption of UV radiation by the lens causes the formation of cataracts (Zigman 1983). Currently, the treatment of choice for cataract surgery is lens removal and implantation of an artificial lens (intraocular lens, or IOL). The popularity of lens-replacement surgery skyrocketed in the 1980s and early 1990s; currently, nearly 1.5 million IOL implant procedures are conducted annually in the U.S. (Daily Apple 1999). By the mid-1990s, approximately 10 million IOLs had been implanted (USHHS 1994). A recent report by the U.S. Department of Health and Human Services (USHHS 2000) reported that, "Cataract extraction with prosthetic IOL insertion is the most common procedure paid for by Medicare.... In 1991, Medicare paid for an estimated 1.14 million IOLs."

There are separate glare problems associated with cataracts and with cataract removal. First, as mentioned in Chapter 2, a cataract both reduces transmission of light into the eye and scatters light as it passes through the lens, creating a veiling luminance effect that reduces contrast sensitivity and increases disability glare. Indeed, headlight glare is often the first sign of cataract development. Removal of the affected lens allows light to reach the retina undisturbed, but the cataract (or lens) removal presents two potential glare side effects.

Edge Glare - Cataract surgery involves the removal of the lens and either IOL implantation or a prescription for contact lenses or eyeglasses. The possible glare effects of corrective lenses that were discussed above apply here as well. In addition, a separate phenomenon has been reported, known as "edge glare" because it results from the edges of IOL implants. This phenomenon is similar to the glare effects resulting from refractive surgery. In the case of cataract surgery, "The glare results from the smaller optical zone and exposure of the IOL edge to the light that will pass through the aphakic capsule peripheral to the optic." (Steinert 1997). In other words, light hitting the edge of the implant often scatters out of the "corner of the eye." Edge glare is a growing concern, as is reflected in comments made by The American Society for Corrective and Refractive Surgery (ASCRS) on the Food and Drug Administration's Draft Intraocular Lens Guidance Document. ASCRS (2000) expressed concern, stating that "unwanted optical images, such as glare, halos, etc,... [have] become an increasingly important visual characteristic associated with the performance of an IOL," and "...in addition to visual acuity, a statement should be made with regard to the overall optical performance of the implant. In particular, the occurrence of unwanted optical images such as glare and halos should be included."

A clinical study on IOL satisfaction (Masket 2000) indicates that there could be additional problems associated with IOL implants, particularly multifocal lenses. Masket asked his patients, "How satisfied are you with your ability to see at night?" Eight of the 20 multifocal lens patients interviewed complained of glare, halos, and starbursts, while only one of the 20 monofocal patients reported such problems.

UV Glare — The second potential problem associated with cataract removal is a largely unaddressed, and at present hypothetical, conflict between the use of UV headlamps as a glare countermeasure and individuals who have undergone cataract surgery. This issue is discussed in some detail above, in the discussion of UV headlamps as a glare countermeasure.

The extent of the potential UV glare problem is difficult to estimate. However, given that windshields absorb most UV radiation and that the population of affected individuals consists mainly of children under 10 years of age and the elderly, disability or discomfort glare from UV headlamps is most likely to have its greatest effect on pedestrians rather than drivers. However, in September 2000 there were approximately 39 million U.S. residents under the age of 10 and, while the number of non-UV-absorbing IOLs in use today is unknown, an unpublished survey (Garvey 1994) estimated it to be around one million.

Advantages

- Correcting refractive error and cataracts may be necessary to meet state requirements to legally operate a motor vehicle and has overall safety benefits, such as improved visual acuity and contrast sensitivity, that also improve a driver's ability to read traffic signs and/or in-vehicle displays.

- For corrective lenses, keeping them clean and free of scratches may minimize the effects of glare—although there is no definitive research to confirm this. Scratch-resistant glasses are available at very little extra cost to the consumer (about $20). Soft contact lenses are available that can be cleaned and rarely scratch, and when they are scratched they can be discarded. Hard contact lenses can be scratched, but the abrasions can be polished out inexpensively (about $10).

- Ophthalmic surgery could grant freedom from corrective lenses, although this is not guaranteed.

- Cataract surgical costs are covered by insurance and Medicare.

- Recent research (Owsley, Sloane, Stalvey, and Wells 1999) found a significant correlation between cataracts and at-fault crash involvement. In other words, drivers with cataracts were more likely to cause an accident than similar drivers who did not have cataracts.

Disadvantages

- Corrective lenses can be lost or scratched. Given their importance to safety, owning a second pair is recommended.

- Refractive eye surgery costs between $1,500 and $5,000 for both eyes. There are risks involved with this surgery besides those related to glare sensitivity. The costs, in addition to the initial surgical expense (which is considered cosmetic and not covered by most insurance plans), include subsequent surgery for further corrections, possible temporary or permanent reduction in contrast sensitivity, and impaired night vision, as well as increased glare sensitivity.

- With cataract surgery, as with any surgical technique, there are risks. If an IOL implant is selected, problems with edge glare can be substantial. However, newly developed lenses with modified edges might help reduce glare occurrence in the future (Holladay, Lang, and Portney 1999).

- At present, UV glare issues are unresolved and hypothetical, as UV headlamps have yet to become a reality.

Summary

A driver must have visual acuity that meets criteria set by the state DMV to legally operate a motor vehicle. In the absence of other contributing pathologies, visual acuity at a distance can usually be corrected inexpensively and safely to meet state requirements by using eyeglasses or contact lenses. Given the importance of vision to safe driving, maintaining these lenses clean and scratch-free is worthwhile, even though the contribution to a reduction in glare may be minimal.

Maintain Minimum Headlamp Area

As mentioned in Chapter 2, a larger glare source will generate a lower discomfort level (all other things being equal), because luminance must be reduced if illuminance at the eye is to be held constant. Although all U.S. headlamps must meet stringent photometric criteria, size and shape are generally unregulated. One consequence of this is that projector-style HID lamps may be contributing to discomfort glare because their surface area is smaller than standard headlamps and so their luminance is much higher. As a countermeasure, some vehicles with HID lamps now incorporate reflectors into the lamps that have a larger area than the lamp.

Discomfort caused by small lamps with large luminance may occur when meeting another vehicle or from mirrors reflecting the image of the headlamp of a following vehicle. Glare from small lamps might also be accentuated when cars are stopped on both sides of an intersection waiting for a light to change. In this situation, there is short viewing distance and long exposure, and, given the idle time, there may be a tendency for drivers to inspect the oncoming lamps more closely.

Research

Sivak et al. (1990) reviewed a paper by Lindae (1970) that concluded headlamp area was important in determining discomfort glare. Lindae recommended a minimum area of 150 cm2 for the European type low-beam headlamp.

Sivak et al. also conducted a laboratory study of the effects of glare illuminance and size on discomfort. Subjects performed a tracking task with the glare source located 15.25 m away and at a glare angle of 3.6 degrees. For a given glare size (sources were either 45.4 or 181.5 cm2), discomfort as measured by the DeBoer scale was a linear function of the logarithm of glare illuminance. This was the expected result, already given by the formula in Chapter 2. The comparison of the two glare sizes revealed a small (0.2 units on the 9 point scale), but significant effect of size on discomfort when illuminance was held constant. The small glare source having greater luminance was more discomforting.

On an actual two-lane road, the glare angle of two opposing vehicles is about 12 degrees, not the 3.6 degrees simulated in the Sivak et al. study. The effect of headlamp size on discomfort glare would therefore be even smaller than that suggested by this study unless the driver chose to look in the direction of the oncoming headlights.

As headlamp size is reduced at any given distance, the lamp becomes more like a point source, for which luminance is not a relevant parameter. Sivak et al. considered the transition between point and extended source to be in a zone the size of a target subtending a visual angle of between 10 minutes and 1 degree. As lamps become smaller, they approach a size at which the eye does not respond to luminance; to maintain a sufficient size for the eyes to respond to luminance, the glare source must be moved closer. With two opposing vehicles, moving the glare source closer will increase the glare angle, which will also reduce the discomfort glare and decrease the likelihood that the driver will look in the direction of the source.

Advantages

- The primary advantage: reduction in discomfort for drivers who choose to look toward the glare source at close distances.

- Reduction in discomfort when looking in the rear-view mirror, when not on the anti-glare setting.

Disadvantages

- Maintaining a minimum headlamp size would constrain the flexibility that designers would like to have to appeal to consumer taste.

- Any physical restrictions on the headlamp may restrict future capability to control the headlamp beam pattern. This restriction could be particularly important for adaptive headlights.

Summary

Given the expected modest impact on glare, there does not appear to be any need to regulate headlamp size. As lamps are made smaller, they become more like a point source and closer distances are required for the eye to respond to luminance; but at closer distances, the glare angle for on-coming vehicles increases, reducing the discomfort glare. Discomfort glare from small headlamps is a potential problem when vehicles meet at intersections; this situation requires further consideration.

Headlamp area is most likely to be an issue with respect to mirror glare, because the distances involved are typically shorter and the visual angle subtended larger than for oncoming vehicles. Although the glare angle is large in the mirror, drivers are likely to look directly at the glare source. Although the luminance as viewed in mirrors has not been studied, anti-glare mirrors could probably be an effective countermeasure. There are few headlamps that are both very small and mounted very high (such as projector lamps in SUVs and pickups), and so, presumably, the problem of small lamps in rear-view mirrors is not severe (Flannagan 2000). However, some of the most recent SUVs are equipped with projector-style lamps, and this could be cause for concern.

CHAPTER 9
SUMMARY AND RECOMMENDATIONS

This report has discussed a wide range of countermeasures that could help mitigate the effects of headlight glare on the vision and discomfort of drivers at night. Many of these countermeasures are effectively used today, but some proposed solutions have regulatory and technological hurdles to surmount before they will be able to resolve the most intractable problems with headlight glare. Within this report, countermeasures were grouped according to method of operation, including such approaches as reducing intensity, reducing illumination, increasing the glare angle, and providing an indirect benefit by some other means. This section will provide a summary of these countermeasures, grouped by who should and who can take a particular action. This section will conclude with a discussion of the research needed to develop and/or justify the use of some of these countermeasures.

Summary of Countermeasures

Countermeasures that can only be initiated by a highway agency include the following:

- Wide medians and independent alignment
- Glare screens
- Fixed roadway lighting

Wide medians, independent alignment, and glare screens are all effective in eliminating glare from oncoming vehicles, either by increasing the glare angle so that the effect of glare is reduced or by blocking glare illumination completely. Wide medians and independent alignment operate primarily in rural and suburban areas, where right-of-way is available, whereas glare screens operate primarily in urban areas, where right-of-way is not available. Wide medians and independent alignment are part of the design process and are not generally remedial treatments that can be subsequently used to counteract glare. While the cost of such measures can be justified by accident reduction alone, the accidents avoided may only be evident when volume has grown much higher than when the road is first designed and built.

Glare screens are a remedial treatment and can be installed when the initial design could not provide sufficient right-of-way for a wide median or when volumes unexpectedly increase over time and worsen the glare and safety problem. Practical limits on height restrict the use of glare screens to relatively flat topography and gentle curvature. Since their effect on the incidence of accidents is not documented, their cost must be justified on the basis of comfort and the expected safety benefits. Glare screens, while effective, are not a cure-all for every glare situation. They are most appropriate where both traffic volume and the demands of the driving task are high, as is often the case on urban arterial roads and in construction work zones with narrow pavement width and concrete barriers that are sometimes difficult to see.

Like wide medians and independent alignment, fixed roadway lighting is often justifiable on the basis of accident reduction alone. However, there is wide variation in the U.S. in the fraction of roads that are lighted. Fixed lighting requires access to electrical power and is generally restricted to urban areas. Installation of fixed lighting also depends on budgets and reflects varying criteria used by highway agencies. The question of whether low-volume roads with low accident rates should be illuminated to minimize the effects of glare is not easily answered. Drivers certainly are more comfortable driving on illuminated roads, and this benefit alone might justify lighting more roads. However, this should be a local decision, made with an understanding of local resources and priorities. Therefore, it is unlikely that all roads with glare problems will ever be illuminated, and until this happens, another solution to the problems introduced by glare must be found.

To the extent that task difficulty is associated with discomfort glare, a variety of road improvements, including alignment, lane width, surface and markings, and so on, may reduce the discomfort experienced from headlight glare.

Countermeasures that are primarily the responsibility of industry are:

- Adaptive headlamps
- Headlamp height
- Headlamp area
- Color-corrected headlamps

Of these four countermeasures, limiting headlamp height is the only one that could be implemented quickly and with little if any cost. Color-corrected headlamps, while offering a low-cost solution, require a significant amount of additional research before adoption. Headlamp area was shown to have little practical consequence, with the possible exception of when drivers are waiting at an intersection. Adaptive headlamps, while theoretically promising, have numerous design, cost, and regulatory obstacles to surmount. While it is clear that adaptive headlamps offer significant improvements to visibility, for example on curves, it is not at all certain what their effect would be on glare. Cost and maintenance issues also need to be resolved before adaptive headlighting becomes a practical countermeasure to glare.

Lowering headlamp height is a promising “no cost” countermeasure to glare, but its impact is limited to mirror glare. With light trucks (including pickups, full-size vans, and sport-utility vehicles) representing 50% of all light vehicle sales, lowering the headlamp height of these vehicles should be pursued and, if appropriate, the conclusions of the SAE task force should be investigated further to establish the impact of lower headlamp height on visibility.

Countermeasures that are under the control of individual drivers are:

- Night-driving glasses
- Anti-glare mirrors
- Corrective vision solutions

Research appears to show that, for most individuals, night-driving glasses are not an effective solution to the glare problem. What is gained in the reduction of discomfort is lost in visibility. This conclusion applies to both full-eye glasses and half-glass analyzers that allow the driver to look through the analyzer only on demand. Although one study suggested that discomfort glare had little effect on driving performance, the measurements of performance were entirely psychomotor and not visual. Research is needed to better understand the relationship, if any, between discomfort and eye fixations, attention, and fatigue.

The conclusion that the loss in visibility from wearing night-driving glasses is not offset by the reduction in discomfort is grounded in the assumption that discomfort results in no immediate performance deficit other than its effect on visibility and the annoyance it causes. This assumption originated in the laboratories and may not be valid on the highway, where people behave differently than they do when sitting in a research laboratory. In addition, although we know how driving affects their rating of discomfort, we do not know how discomfort glare affects eye fixations, attention, and fatigue. There is research that suggests that drivers’ eyes are attracted to light but are drawn away from glare sources. Additional research is needed to support or deny the assumptions being made and the conclusion that night-driving glasses (including half-glass analyzers) have no value for anyone driving at night.

Anti-glare mirrors, together with limits on headlamp height and enforcement of standards for headlight aiming are all that is needed to control mirror glare created from passing or following vehicles. Until all vehicles are equipped with some type of automatic glare-reduction mirrors in both the rear-view and left side positions—and we do not doubt that this will happen—drivers need to be encouraged to use the night setting of their prism mirrors and to aim the left outside mirror so that it does not reflect directly in their eyes. The question of what drivers need to see in their rear-view mirrors needs further study so that automatic glare reduction mirrors can be properly designed and drivers believe that they are seeing everything that is necessary.

Vision correction should be encouraged to benefit visibility but reduction in glare would be minimal.

Countermeasures that will require government involvement include:

- Changing beam photometric distribution
- Maintenance of headlight aim
- License restriction
- Ultraviolet headlights
- Polarized headlighting

Any major modification to the low-beam photometric distribution must be made by the federal government by means of FMVSS 108. As discussed in this report, the last modification, in 1997, included some minor changes to allow a sharper cutoff for VOA headlamps. This modification has resulted in development of some headlamps that produce less light above the horizontal, threatening a potential reduction in the illumination for signs. Attempts to achieve a standard which harmonizes ECE and U.S. requirements have not proven successful. Every effort to reduce headlamp illumination or change the beam pattern has been met with concern about visibility, and every effort to increase illumination has been met with concern about glare. Research does not support any change in either direction, any more than the research supports the use of the current beam pattern. The present standard is a compromise that has evolved over time and that works reasonably well; the risks of making any major change appear too great. Therefore, any effort to develop countermeasures for glare should focus on one or more of the other alternatives discussed in this report.

While one might think that maintenance of headlight aim is a countermeasure that could be implemented by the driver, there is generally little incentive for drivers to do so. A driver is likely to correct his own misaimed headlamps only when they are not providing adequate visibility of the road ahead, and in this situation they are usually not creating a glare problem. If misaimed headlamps are creating a glare problem, the driver is likely to think they are fine, because for the driver increased glare production is associated with improved visibility.

Misaimed headlamps are the most problematic source of headlight glare. Without an enforced limit to the amount of misaim, it is impossible to define the worst case that any glare countermeasure must remedy. The introduction of VOA headlamps has made it easier to detect misaim, but does not provide any incentive to correct problems. While regulation of vehicle inspection is thought to be a state issue, federal involvement may be appropriate for vehicles that cross state lines.

Driving restriction through license restricture, while not a viable alternative from either a political or practical perspective, may be effective if self-enforced. Older drivers can be sensitized to understanding their limitations by relatives and family physicians as well as through older driver education courses.

Ultraviolet lighting has some potential to reduce headlight glare, but only indirectly. This technology should and will be pursued primarily because of its benefits to vision, particularly vision under adverse conditions such as rain, snow, and fog, but it is not likely to replace conventional lighting and so cannot offer a realistic countermeasure to glare.

Of all the countermeasures discussed in this report, polarized lighting is the one that could eliminate glare entirely and make the nighttime road a friendlier place to travel. With the advent of HID lamps, the very technology that has heightened the glare problem offers the ultimate final solution. With polarized lighting, the tradeoff between visibility and glare is resolved, and we can have our cake and eat it without recrimination. It appears that the only real obstacle to pursuing this countermeasure further is the difficulty of implementation.

Research Needed

In addition to the countermeasures discussed in this report, there are a vast number of patented products in various stages of development. Many are for products that offer enhancements to the countermeasures already discussed. Unfortunately, it is beyond the scope of this report to explore the potential of all of these concepts. Hopefully, those ideas that offer useful solutions to the glare problem will gradually find their way into commercial products.

Two of the potential countermeasures discussed in this report are being studied in large ongoing research programs. Adaptive headlamp technology is being developed and strategies for its implementation are being devised with the support of several European countries and manufacturing firms. In the U.S., a comprehensive research program for the development and implementation of UVA headlamps is underway. Both adaptive headlighting and UVA headlamps are more likely to benefit visibility than to offer any comprehensive solution to headlight glare.

Topics that are not currently being investigated but which should be include one countermeasure (polarized lighting); the effects of the spectral content of light on visibility and discomfort at mesopic adaptation levels; the relative effectiveness of electrochromic, photochromic and neodymium mirrors on glare sensation and rearward visibility; the identification of the population of drivers most affected by glare and the reasons for their problems with headlight glare; and a more complete description of the behavioral effects of discomfort glare.

Polarized Headlighting

It seems that polarized lighting is the only countermeasure for headlight glare which has the potential to be used in all situations and resolve all problems. Research has shown that headlamp intensity must be doubled before polarized lighting would be feasible; however, HID lamps offer three times the intensity of ordinary headlamps and can easily meet this requirement. Thus, the only remaining challenge is developing a strategy for implementation.

Hemion, Hull, Cadena, and Dial (1971) suggested that a large-scale public test of polarized lighting should be conducted to observe first-hand the public's reaction, as well as to determine the benefits, side effects, and operational problems that would result from a change to polarized headlights. This test should take place at a site with a good cross-section of the country's motoring public but which can also be kept essentially isolated from the intrusion of vehicles having normal headlights (Hemion 1969b). An ideal site would be an island that could only be accessed by ferry or boat and where incoming, unmodified vehicles could be modified before interacting with traffic.

During a delay while developing the plans for such a test, Hemion (1971) conducted a small-scale test of 120 drivers. As explained in Chapter 6, the results of this small-scale study showed that the benefits outweighed the deficiencies of the system. After completing the small-scale study, the authors recommended that, in order to achieve clarification in the areas of system development, operation, and performance, the goals of a large-scale test should include the following:

- To determine the most effective mode of polarization during and after the transition period, from the following possibilities:
  (1) Polarized high beams with unpolarized low beams;
  (2) High and low beams polarized;
  (3) Polarized high beam for use on rural, unlighted roadways with unpolarized, low-intensity low beam for urban, lighted roadway use;

(4) Unpolarized high beam for open road operation with polarized high beam for meeting other vehicles on rural, unlighted roads and unpolarized, low-intensity low beam for urban, lighted roads.

- To compare the consequences of an extended transition period for conversion to polarization with the consequences of a simultaneous, “common-date” conversion.
- To determine the extent to which headlight polarization beneficially or adversely affects traffic factors such as traffic flow, accidents, vehicle utilization, and vehicle maneuvers.

- To determine the extent to which polarization beneficially or adversely affects vehicle operation and maintenance requirements, including such factors as battery and generator life, battery charge, system voltage, lamp life, polarizer and analyzer life, windshield depolarization, and headlamp aim and reaim requirements.

Exploration of the Spectral Content of Light

As indicated in Chaptert 5, more study is warranted on the effects that varying the spectral content of light would have on visibility, driver discomfort, and fatigue. Tradeoffs between gains and losses in visibility need to be compared with changes in discomfort glare before any significant changes are made to the spectral content of headlighting.

Effectiveness of Electrochromic, Photochromic, and Neodymium Mirrors on Glare Sensation and Rearward Visibility

Additional research is needed to evaluate the tradeoffs between rearward visibility, forward visibility, and discomfort glare for the three competing automatic control systems for mirror glare discussed in Chapter 6: electrochromic, photochromic, and neodymium mirrors. Studies should help to determine the appropriate levels of reflectivity, what rearward visual information drivers need, and the nature of any luminous or spectral filtering under various conditions. Optimization algorithms are needed for each new technology to ensure that efforts to minimize discomfort do not result in the obscuring of critical stimulus elements, such as original color or the content of a changeable message sign (CMS).

Identification of the Population of Drivers Affected and the Basis of Complaints about Headlight Glare

Although glare from automotive headlamps has been a concern from the time they were first used, only in the past few years have public complaints become highly vocal. What fundamental change has occurred to make the problems with headlight glare so serious? Higher headlamp mounting heights, which are associated with an increase in the number of SUVs, and HID headlamps, along with their cosmetic after-market derivatives, are most often the recipients of blame. However, other factors may make significant contributions to the problem, particularly increased traffic volume, headlamp misalignment, and an aging population. Research identifying the contribution of each factor to the increase in complaints about headlight glare would help direct efforts to find appropriate countermeasures.

In addition to learning the basis for complaints about headlight glare, research should seek to identify who is complaining. At a minimum, the information obtained would include the age, sex, and urban/rural driving patterns of those voicing complaints. One very plausible reason for the increasing complaints about glare is the aging of the population—the number of older drivers is increasing, as is the average age of all drivers. While the relationship between age and discomfort glare is inconclusive, age is related to the incidence of cataracts and bears a relationship to a variety of other measures of visual performance. If an analysis of complaints were to show a disproportionate representation among older drivers, the appropriate countermeasure might be to pursue voluntary restrictions on night driving.

While an understanding of complaints about headlight glare is important, it must be remembered that disability glare problems may exist even in the absence of complaints about discomfort. Many drivers who are not significantly bothered by glare from headlamps may nonetheless suffer significant decrements in visibility and not be aware of the loss.

Description of the Behavioral Effects of Discomfort Glare

A detailed discussion of discomfort glare was presented in Chapter 2. For some time the accepted definition of discomfort glare has been the 9-point DeBoer scale, where discomfort is rated from 1 (unbearable) to 9 (just noticeable). The criterion typically used in making judgements of discomfort glare is that the rating should be 5 (just acceptable) or greater. The vocal complaints about headlight glare are presumed to reflect experiences of glare rated 4 or lower.

While it may be worthwhile to attempt to reduce the number of complaints about glare, any cost-benefit analysis must identify how the reduction in complaints will be accompanied by behavioral changes that would improve safety. Whenever discomfort glare is used as the criterion for evaluating a countermeasure, it would be valuable to know how the level of discomfort glare relates to driving performance, for example by causing drivers to look away from the road or by producing a reduction in alertness mediated by fatigue. Theeuwes and Alferdinck (1996) found no relationship between discomfort glare and speed reductions, but they did not consider the effect of discomfort glare on fatigue or on the direction of the driver's attention.

In the discussion of night-driving glasses in Chapter 6, the possibility was raised that the half-glass analyzer might be used only when the discomfort is so great that the choice is between looking off the road, seeing the road peripherally without glasses, or looking straight ahead with foveal vision reduced by the glasses. Without the knowledge of how discomfort relates to visual acuity, the potential usefulness of night-driving glasses cannot be dismissed. Research is needed to quantify the effects of discomfort glare on driver fixations and overall alertness, and specifically to determine whether the half-glass night driving analyzer can offer a net benefit in reducing fatigue and/or enabling drivers to keep their eyes on the road.

Education May Reduce Complaints of Glare

Several organizations, including AAA, AARP and the National Safety Council offer refresher courses for older drivers. While not presented as a legitimate countermeasure, these programs make a number of recommendations for reducing the problem of glare from headlights. The most basic solution suggested by this course is to simply

- Avoid night driving

and, if you must drive at night,

- Limit night driving to well-lit roadways,
- Increase following distance,
- Avoid looking into headlights—look slightly to the right of glaring headlights.

These courses also recommend some actions that relate to countermeasures discussed in this report.

- Position outside mirrors so the headlights of following cars are not directed into your eyes.
- Do not wear colored lenses, anti-glare glasses, or sunglasses for night driving, unless directed to do so by an eye doctor.
- Keep headlights, taillights, windshields (inside and out), and your eyeglasses clean.
- Keep headlights properly adjusted.
- Have eye examinations, frequently, by a licensed ophthalmologist or optometrist.

Conclusions

One countermeasure that has been proposed is the elimination of HID lamps. The application of HID in both the UVA and polarized headlamp systems is a reason to remain active in this technology, but the elimination of low-beam HID lamps by government regulation may be an appropriate step to control glare, if these lamps are indeed the source of glare problems. Although HID lamps offer an enormous increase in visibility, they can also result in a comparable increase in glare.

Properly aimed and cleaned, they should be able to deliver improved visibility without excessive glare on roads without curvature; however, if these lamps become dirty, are misaimed, or are encountered on vertical or horizontal curves, the amount of glare can exceed levels considered tolerable. Such conditions result in glare with all headlamps, but the greater flux from HID sources will produce more glare when the lamps are dirty, and their greater illumination on some beam angles will result in more glare if they are misaimed. If HID lamps are kept aimed and clean, they are likely to produce a net gain in performance and visibility with minimum discomfort; but if such steps are not taken, their removal from U.S. highways may be an appropriate countermeasure. This point was clearly made by Schoon & Schreuder (1993).

Still, the proper operation or removal of HID lamps will not solve all problems of headlight glare, nor would universal participation in older driver training courses. The design and selection of countermeasures for headlight glare are included in the basic tradeoffs that are incorporated in the design of headlamps. As discussed in Chapter 5, the U.S. standard design, compared to the European standard, favors visibility over glare. The U.S. standard, which began as a conceptual exercise, has, over time, determined the design of traffic control devices. Many devices have been designed under the assumption that they will receive minimum levels of illuminance from headlights at the same locations in the beam pattern that also illuminate mirrors or the eyes of drivers in oncoming vehicles. In this way, the highway infrastructure places restrictions on any manipulation of the beam pattern to reduce glare. Each countermeasure discussed in this report offers limited benefits in special situations, but, as stated earlier, only polarization provides a global solution. We hope that research in that area will go forward with as much dedication as is being devoted to the research and development of UVA and of adaptive headlighting.

It is not possible to recommend one countermeasure that would eliminate discomfort glare for everyone in all situations without unacceptable negative consequences for visibility and safety. However, a number of the countermeasures discussed can be implemented with minimal cost or with costs offset by benefits other than glare reduction. Fixed roadway lighting, glare screens, and wide medians are, in certain situations, cost-effective methods of accident reduction regardless of their effect on adaptation and glare. It would make the most sense to start simply by initiating those strategies that can be implemented with minimal or no cost. Maintenance of corrective lenses or ophthalmic surgery, remedial driver education, and self-imposed restrictions on night driving offer many safety advantages beyond their effects on glare. Some limitation on headlamp height, coupled with the use of anti-glare mirrors and better maintenance of headlamp aim, would eliminate most, if not all, complaints of mirror glare. Finally, UVA and adaptive headlighting still need to be pursued, but their benefits and costs will not be known until these approaches are fully developed. At the present time, UVA and adaptive headlighting appear to offer greater promise for improving visibility than for reducing glare, but more development and further evaluation will give a better picture of the benefits. Polarized lighting seems to offer the most promise for eliminating glare, but the obstacles to implementation may prevent this technology from becoming reality.

REFERENCES

AASHTO (1994). *A policy on geometric design of highways and streets*, American Association of State Highway and Transportation Officials, Washington, DC pp. 136–137.

Adler, B. and Lunenfeld, H. (1973). “Three-beam headlight evaluation.” Report no. HS-238-411-1, Airborne Instruments Laboratory, Deer Park, NY.

Adrian, W. K. (1975). “Grundlagen der physiologischen und psychologischen Blendung und ihre numerische Darstellung” (Fundamentals of disability and discomfort glare and their numerical representation). *Lichttechnik* **27**, 312–319.

Adrian, W. K. (1979). “Ueber eine neuartige Blendschutzbrille” (On a new anti-glare spectacle). 30. Sonderderuck der WVAO, Mainz.   Die Fachvortrage des WVAO - Jahres Kongresser 1979 in Karlsruhe (ISSN 0171-6417), pp. 243–251.

Adrian, W. K. (1991a). “Transient adaptation process: A model to predict its effects on vision.” *CIE 22nd Session*, **2**, 121–133.   CIE transactions of the International Commission on Illumination, 22nd session. Melbourne 1991, Vol 2, pp 121-133.

Adrian, W. K. (1991b). “Comparison between the CBE and the CIE glare mark formula and earlier discomfort glare descriptions.” *Proceedings of the First International Symposium on Glare, Orlando, Florida*, pp. 155–164.

Adrian, W. (1997). “A method to predict visual function and visual performance in mesopic lighting levels.” University of Waterloo, Ontario, Canada.

Adrian, W. and Bhanji, A. (1991). “Fundamentals of disability glare. A formula to describe stray light in the eye as a function of the glare angle and age.” *Proceedings of the First International Symposium on Glare, Orlando, Florida*, pp. 185–194.

Alexander, G. J. and Lunenfeld, H. (1990). “A users’ guide to positive guidance, third ed.” Report No. FHWA-SA-90-017, U.S. Department of Transportation, Federal Highway Administration, Washington, DC pp. 1–39.

Allen, M. J. (1985). “Vision of the older driver: implications for vehicle and highway design and for driver testing.” 55+, 1–7.

Anderson, R. M. (1983). “Visual perceptions and observations of an aphakic surgeon.” *Perceptual and Motor Skills*, **57**, 1211–1218.

Applegate, R. A. (1991). “Acuities through annular and central pupils after radial keratotomy (RK).” *Optometry and Vision Science*, **68**, 584–590.

Applegate, R. A. and Gansel, K. A. (1990). “The importance of pupil size in optical quality measurements following radial keratotomy (RK).” *Refractive and Corneal Surgery*, **6**, 47–54.

Applegate R. A., Hilmantel, G., and Howland, H. C. (1996). “Corneal aberrations increase with the magnitude of radial keratotomy (RK) refractive correction.” *Optometry and Vision Science*, **73**, 585-589.

Applegate, R. A., Trick, L. R., Meade, D. L., and Hartstein, J. (1987). “Radial keratotomy (RK) increases the effects of disability glare: Initial results.” *Annals of Ophthalmology*, **19**, 293–297.

ASCRS (2000). American Society of Cataract and Refractive Surgery, “Comments on FDA’s draft intraocular lens guidance document,” available at *http://www.ascrs.org/advocacy/fdaioljan00.htm.*

Bailey, I. L. and Sheedy, J. E., (1986). “Vision screening for driver licensure.” *Transportation in an Aging Society*, pp. 294–323. Transportation Research Board, National Research Council, Washington, DC 1988.

Bennett, C. A. (1977). “The demographic variables of discomfort glare.” *Lighting Design and Application*, 22–24. January, 1977.

Berman, S. M. (1992). “Energy efficiency consequences of scotopic sensitivity.” *Journal of the Illuminating Engineering Society*, **21**(1). Volume 21, 3-14.

Berman, S. M., Fein, G., Jewett, D. L., and Ashford, F. (1993). “Luminance controlled pupil size affects Landolt G test performance.” *Journal of the Illuminating Engineering Society*, **22**, 150–165.

Berman, S. M., Fein, G., Jewett, D. L., and Ashford, F. (1994). “Landolt C recognition in elderly subjects is affected by scotopic intensity of surround illuminants.” *Journal of the Illuminating Society*, **23**, 123–130.

Berman, S. M., Fein, G., Jewett, D. L., Benson, B. R., Law, T. M., and Myers, A. W. (1996). “Lighting spectral effects on Landolt C performance is abolished by mydriasis.” *Journal of the Illuminating Society*, **25**, 42-50.

Berman, S. M., Jewett, D. L., Benson, B. R., and Law, T. M. (1997). “Despite different wall colors, vertical scotopic illuminance predicts pupil size.” *Journal of the Illuminating Engineering Society*, **26**, 59–68. Volume 26, Summer, 1997.

Bhise, V. D., Farber, E. I., Saunby, C. S., Troell, G.M., Walunas, J. B., and Bernstein, A. (1977). “Modeling vision with headlights in a systems context.” Society of Automotive Engineers, International Automotive Engineering Congress and Exposition. Cobo Hall, Detroit. February 28-March 4, 1977.

Bhise, V. D., Matle, C. C., and Hoffmeister, D. H. (1984). “CHESS model application in headlamp systems evaluation.” SAE Technical Paper Series #84046, Society of Automotive Engineers, Warrendale, PA.

Billion, C. E. and Parsons, N. C. (1962). “Median Accident Study—Long Island, New York.” *Bulletin 308*, Highway Research Board, National Research Council, Washington, DC, pp. 64–79.

Blackwell, H. R. (1954). “Visual detection at low luminance through optical filters.” *Highway Research Board Bulletin No. 89*, National Academy of Sciences, Washington, DC, pp. 43–61.

Bouma, P. J. (1938). “The colour reproduction of incandescent lamps and ‘Philiphane Glass’.” *Philips Technical Review*, **3**, 27–29.

Box, P. C. (1973). “Freeway accidents and illumination.” *Highway Research Record*, **416**, 10– 20.

Boyce, P. R. (1981). *Human Factors In Lighting*. MacMillan, New York, NY.

Boyce, P. R. and Beckstead, J. W. (1991). “Influences on discomfort glare ratings.” *Proceedings of the First International Symposium on Glare, Orlando, Florida*,pp. 93–100.

Boyce, P. and Bruno, L. (1998). “An evaluation of high pressure sodium and metal halide light sources for parking lot lighting.” *Proceedings of the IESNA*, San Antonio. Illumination Engineering Society of North America

Bryan, W. E. (1962). “Lenses for night driving.” *Highway Research Board Bulletin No. 336*, National Academy of Sciences, Washington, DC, pg. 104.

Caden, D. G. and Hemion, R. H. (1969). “Disability glare effects from vehicle headlights and fixed overhead street lighting.” *Final Report on Phase IV-B of FHWA Contract CPR 11-4126*, Report No. AR-700, Southwest Research Institute, San Antonio, TX. p. 1-23.

Chu, X. (1994). “The Effects of age on the driving habits of the elderly. Evidence from the 1990 National Transportation Study” Contract No. DOT-T-95-12, U.S. Department of Transportation Research and Special Programs Administration, Washington, D.C.

Consumer Reports (1999). “Zap your myopic eyes? Laser surgery is booming—but pitfalls persist.” *Consumer Reports*, June 1999, pp. 56–57.

Copenhaver, M. J. and Jones Jr., R. E. (1992). “Measurement of headlamp aim and the electrical and photometric performance characteristics of rear lighting systems.” DOT HS 807 930, U.S. Department of Transportation, National Highway Traffic Safety Administration, Washington, DC.

Crawford, B. H. (1936). “The integration of the effects from a number of glare sources.” *Proc. Phys. Soc. London* 48. p. 35.

Crosby. J. R. (1960). “Cross-median accident experience on the New Jersey Turnpike.” *Bulletin 266*, National Research Council, Highway Research Board, Washington, DC, pp. 63–77.

Daily Apple (1999). Available at *http://thedailyapple.com/.*

DeBoer, J. B. and Schreuder, D. A. (1967). *Transportation Illuminating Engineering Society (London)*, **32**, 117.

DHHS (2000). “Acquisition cost of prosthetic intraocular lenses.” U.S. Department of Health and Human Services, Office of Evaluation and Inspections, Washington, DC. Available at *http.//www.dhhs.gov/.*

Duncan, D. D. (1996). “Nighttime glare reduction and illumination enhancement.” Report No. FS-96-037, Johns Hopkins Applied Physics Laboratory, Fleet Systems Department, pp. 1–35.

Farber, E., Gallagher, V., and Cassel, A. (1971). “Interaction between fixed and vehicular illumination systems—Phase I Report,” FHWA Contract No. FH11-7599, U.S. Department of Transportation, Federal Highway Administration, Washington, DC.

Fatality Analysis Reporting System (FARS). National Highway Traffic Safety Administration, National Center for Statistics and Analysis. Available at http://www.nhtsa.dot.gov/people/ncsa/.

Fast, P. T. and Ricksand, A. (1994). “Safer nighttime driving, UV headlamps improve visibility of pedestrians.” Paper No. 94-0908, Presentation at the Transportation Reseach Board 73rd Annual Meeting,, Washington, DC. January, 1994. Transportation Research Board, Washington, D.C.

Federal Register (1995). “Lamps, reflective devices and associated equipment; establishment of negotiated rulemaking advisory committee.” 49 CFR Part 571, National Highway Traffic Safety Administration, Washington, DC. Vol. 60, No. 111, Friday, June 9, 1995.

Federal Register (1997). “Federal motor vehicle safety standards; lamps, reflective devices and associated equipment.” 49 CFR Part 571, National Highway Traffic Safety Administration, Washington, DC. Vol. 62, No. 46, Monday, March 10, 1997.

Finsterwalder, Josef (1991). Untersuchungen zur Physiologischen blendung bei sehr Kleinen Blendwinkeln. (“Investigations on Disability Glare at Very Small Glare Angles”). Ph.D. thesis at the Faculty of Physics of the Ludwig-Maxililian University, Munich, Germany.

Flannagan, M. (2000). Michael Flannagan, Personal Communication, October 2000.

Flannagan, M. J., Gellatly, M. J., Luoma, J., and Sivak, M. (1992). “A field study of discomfort glare from high-intensity discharge headlamps.” Report No. HS-041 319, UMTRI-92-16, University of Michigan Transportation Research Institute, Ann Arbor, MI.

Flannagan, M. and Sivak, M. (1990). “Nighttime effectiveness of rearview mirrors: Driver attitudes and behaviors.” SAE Technical Paper Series #900567, Society of Automotive Engineers, Warrendale, PA.

Flannagan, M., Sivak, M., and Gellatly, A. W. (1991). “Rearward vision, driver confidence, and discomfort glare using an electrochromic rearview mirror.” SAE Technical Paper Series #910822, Society of Automotive Engineers, Warrendale, PA.

Flannagan, M.J., Gellatly, M.J., Luoma, J., and Sivak, M. (1992). A field study of discomfort glare from high-intensity discharge headlamps. University of Michigan Transportation Research Institute, Ann Arbor. Industry Affiliation Program for Human Factors in Transportation Safety. Report No. UMTRI-92-16. UMTRI-82468.

Flannagan, M. J., Sivak, M., and Traube, E. C. (1994). “Discomfort glare and brightness as a function of wavelength.” Report UMTRI-94-29, University of Michigan Transportation Research Institute, Ann Arbor, MI.

Flannagan, M. J., Sivak, M., Traube, E. C., and Kojima, S. (1996). “Effects of overall low-beam intensity on seeing distance in the presence of glare.” Report UMTRI-96-26, University of Michigan Transportation Research Institute, Ann Arbor, MI., pp. 1–26.

Fisher, A. J. (1970). “A basis for a vehicle headlighting specification.” *IES Lighting Review* **32**, 1–9.

Fry, G. A. (1953). Presented to the light and vision conference, June 1953, University of Michigan. *Journal of the Optical Society of America* **43**(3), 189-195.

Fry, G. A. (1954). “Evaluating disabling effects of approaching automobile headlights.” *Highway Research Bulletin 89, Night Visibility,* pp. 38–42. Highway Research Board Bulletin, 89, 38-42.

Fry, G. A. and King, V. M. (1975). “The pupillary response and discomfort glare.” *Journal of the Illuminating Engineering Society* **4**, 307.

Fugate, J. M. and Fry, G. A. (1956). “Relation of changes in pupil size to visual discomfort.” *Illumination Engineering* **L1**, 537-549.

Garner, G. R. and Deen, R. C. (1973). “Elements of median design in relation to accident occurrence.” In *Highway Research Record 432*, National Research Council, Highway Research Board, Washington, DC, pp. 1–11.

Garvey, P. M. (1994). “Potential adverse effects of UV automobile headlamps on children, aphakes, and non-UV absorbing pseudophakes.” Grant Submission to the National Institutes of Health, National Eye Institute, Bethesda, MD (personal communication).

Ghaith, A. A., Stulting, D. J., Thompson, K. P., and Lynn, M. (1998). “Contrast sensitivity and glare disability after radial keratotomy and photorefractive keratectomy.” *Archives of Ophthalmology* **116**, 12-18.

Gouras, P. and Zrenner, E. (1981). “Color Vision: A review from a neurophysiological perspective.” In *Progress in Sensory Physiology 1,* Springer, NY, pp. 139–179.

Ham, W. T., Mueller, H. A., Ruffolo, J. J., and Guerry, D. (1980). “Solar retinopathy as a function of wavelength: Its significance for protective eyewear.” In *The effects of constant light on visual processes,* T. P. Willams and B. N. Baker, eds., Plenum, NY, pp. 319–346.

Hammer, H. M., Yap, M., and Weatherill, J. R. (1986). “Visual performance in pseudophakia with standard ultraviolet-absorbing intraocular lenses: A preliminary report.” *Transactions of the Ophthalmological Society of the United Kingdom*, **105**, 441–446.

Haney, J. E. and Mortimer, R. G. (1974). “Toward more effective headlighting.” Report No. UM-HSRI-RI-74-2, University of Michigan Highway Safety Research Institute, Ann Arbor, MI.

Hare, C. T. and Hemion, R. H. (1968). “Headlamp beam usage on U.S. highways.” Report No. AR-666, Contract No. CPR11-4126, U.S. Department of Transportation, Federal Highway Administration Bureau of Public Roads, pp. 1–82.

Hartmann, E. and Moser, E. A. (1968). “Das Gesetz der physiologischen Blendung bei sehr kleinen Blendwinkeln.” *Lichttechnik* **10**, 67A.

Helmers, G., Ytterbom, U., and Lundkvist, S. O. (1993). “Detection distances to obstacles on the road when using UV headlights.” Statens Vaeg-och Transportforskningsinstitut, Stockholm, Sweden.

Hemion, R. H. (1969a). “A preliminary cost-benefit study of headlight glare reduction. Final Report on Phase V of a Study for the Bureau of Public Roads, Federal Highway Administration, Contract No. CPR 11-4126, SWRI Project No. 11-1908.” Southwest Research Institute, San Antonio, TX.

Hemion, R. G. (1969b). “Preliminary site selection for public test of polarized headlighting. Report on Phase VI of a Study for the U.S. Bureau of Public Roads.” Report No. AR-692, Southwest Research Institute, San Antonio, TX.

Hemion, R. H., Hull, R. W., Cadena, D. G., and Dial, B. C. (1971). “Development of plans for public evaluation of polarized headlights.” Final Report No. AR-815, Contract No. FH 11-7349, U.S. Department of Transportation, Federal Highway Administration, Washington, DC, pp. 1–110.

Hogrefe, H. and Neumann, R. (1997). “Adaptive light pattern—A new way to improve light quality.” SAE Technical Paper Series #970644, Society of Automotive Engineers, Warrendale, PA.

Holladay, L. L. (1926). “The fundamentals of glare and visibility.” *Journal of the Optical Society of America*, **12**, 271–319.

Holladay, J. T., Lang, A., and Partney, V. (1999). “Analysis of edge glare phenomena in intraocular lens edge designs.” *Journal of Cataract and Refractive Surgery*, **25**. Available at http.//www.ascrs.org/publications/jcrs/absjun9.htm.

Hopkinson, R. G. (1963). *Architectural Physics: Lighting*. Her Majesty’s Stationary Office, London, UK.

Hunt, J. H., Land, E. H., and Roper, V. J. (1948). “The polarized headlight system.” *HRB Bulletin 11*, National Research Council, Highway Research Board, Washington, DC.

Hurd, F. W. (1957). “Accident experience with traversable medians of different widths.” *Bulletin 137*, National Research Council, Highway Research Board, Washington, D.C., pp. 18–26.

Hutchinson, J. W., Kennedy, T. W., and Scott, W. A. (1963). “Medians of divided highways: Current status of knowledge and annotated bibliography.” *Highway Research Board Bibliography*, **34**, 2–5.

Ijspeert, J. K., et al. (1990). “The intraocular straylight function in 129 healthy volunteers; Dependence on angle, age and pigmentation.” *Vision Research*, **30**, 699-707.

Institute for Road Safety Research (1976). “White or yellow lights for vehicle headlamps?” Institute for Road Safety Research Report, Leidschendam, Netherlands.

Janoff, M. S. (1999). “The effect of lamp color on driver visual performance: A summary of recent research.” Roadway Lighting Committee Papers Symposium, Birmingham, AL.

Janoff, M. and Havard, J. (1997). “The effect of color on the visibility of small targets.” *Journal of the Illuminating Society*, **26**. Vol. 26, No. 1, 173-181.

Johansson, G., Bergstörm, S.-S., Jansson, G., Ottander, C., Rumar, K., and Ornbergt, G. (1963). “Visible distances in simulated night driving conditions with full and dipped headlights.” *Ergonomics* **6**, 171–179.

Karpen, D. (1996). “Color corrected motor vehicle headlight.” U.S. Patent No. 5,548,491.

Karpen, D. (1998a). “Motor vehicle rearview mirror.” U.S. Patent No. 5,844,721.

Karpen, D. (1998b). “The road less traveled.” LD+A, 47–50. Journal, July 1998.

Karpen, D. (1999). “ Color corrected high intensity discharge motor vehicle headlight.” U. S. Patent #5,961,208, pp. 1–14.

Karpen, D. (2001). “Neodymium oxide doped headlight lamps.” Report No. 2001-01-0319, Society of Automotive Engineers, Detroit, MI, pp. 1–7.

Kinsey, V. E. (1948). “Spectral transmission of the eye to ultraviolet radiation.” *Archives of Ophthalmology* **39**, 508– 513.

Knuiman M. W., Council, F. M., and Reinfurt, D.W. (1993). “Association of median width and highway accident rates.” In *Transportation Research Record 1401*, National Research Council Transportation Research Board, Washington, DC, pp. 70–-80.

Kobayashi, S., Takahashi, K., and Yagi, S. (1997). “Development of new forward lighting systems with controllable beams.” SAE Technical Paper Series #970646, Society of Automotive Engineers, Warrendale, PA.

Kozak, E. M. (1996). “Feasibility of UV-activated fluorescent materials.” Draft Final Report, Federal Highway Administration, McLean, VA.

Lauer, A. R. (1951). “Filter study of the effect of certain transmission filters on visual acuity with and without glare.” *Highway Research Board Bulletin No. 43,* National Academy of Sciences, Washington, DC, pp. 45–51

Leibowitz, H. W. and Owens, D .A. (1978). “New evidence for the intermediate position of relaxed accommodation.” *Documenta Opnthamologica,* **46**, 133–147.

Lerman, S. (1983). “An experimental and clinical evaluation of lens transparency and aging.” *Journal of Gerontology,* **38**(3), 293–301.

Lewis, A. (1997). “Visual performance as a function of spectral distribution of light sources at illuminances used for outdoor lighting.” *Journal of the Illuminating Society*, in press.

Lewis, A. (1998). “Equating light sources for visual performance at low luminances.” *Journal of the Illuminating Society,* **27**. p. 80-84.

Lindae, G. (1970). “Optimale Scheinwerfergrosse fur europaisches Abblendlicht” (Optimum size of headlamps for the European low beam). *ATZ Automobiltechnische Zeitschrift,* **72**, 427– 431.

Lulla, A. B. and Bennett, C. A. (1981). “Discomfort glare: Range effects.” *Journal of Illuminating Engineering Society,* **10**, 74-80. January, 1981.

Manassero, G., Paolini, A., Battaglino, S., Bigliati, C., and Sinesi, S. (1999). "Adaptive lighting systems: Technical solutions and a methodological approach for photometric specifications." progress in automobile lighting. Department of Lighting Technology. 514–525. Volume 6, Progression Automobile Lighting, Department of Lighting Technology, Published by Prof. Dr. Ing. H.-J. Schmidt-Clausen, Darmstadt University of Technology.

Mehra, M. et al. (1998). "A field study of visual acuity, color naming and visual search under mesopic lighting." *Proceedings of the IESNA,* San Antonio, TX.

Miller, D. and Lazenby, G.W. (1977). "Glare sensitivity in corrected aphakes." *Ophthalmic Surgery,* **8**, 54–57.

Miller, N. D., Baumgardner, D., and Mortimer, R. G. (1974). "An evaluation of glare in nighttime driving caused by headlights reflected from rearview mirrors." Report No. 740962, Automobile Engineering Meeting, Society of Automotive Engineers, Warrendale, Automobile Engineering Meeting, Oct. 21-25, 1974.

Mortimer, R G. (1974). "Some effects of road, truck and headlamp characteristics on visibility and glare in night driving." Report No. 740615, Society of Automotive Engineers, Warrendale, PA.

Mortimer, R. G. (1988). "Headlamp performance factors affecting the visibility of older drivers in night driving." In *Transportation in an Aging Society: Improving Mobility and Safety for Older Persons, Special Report 218,* Vol. 2, pp. 379–403. Committee for the Study on Improving Mobility and Safety for Older Persons, Transportation Research Board, Washington, DC.

National Safety Council (1988). *Accident Facts*, National Safety Council, Washington, DC pp. 49–58.

National Safety Council (1990). *Accident Facts*, National Safety Council, Washington, DC, pg. 60.

National Safety Council (1994). *Accident Facts*, National Safety Council, Washington, DC, pg. 64.

National Safety Council (1999). *Injury Facts*, National Safety Council, Washington, DC, pg. 90.

National Transportation Statistics (1999). "National Transportation Statistics." U.S. Department of Transportation. Available at *http://www.bts.gov/ntda/nts/NTS99/data/Chapter1/1-29*.

NCHRP Report 77 (1979). Page 19.

NHTSA (1987). *Fatal accident reporting system,* HS 807 360. U.S. Department of Transportation, National Highway Traffic Safety Administration, Washington, DC

Nitzburg, M., Seifert, R., Knoblauch, R., and Turner, D. (1998). "A safety evaluation of UVA vehicle headlights." Report No. FHWA-RD-99-079, Center for Applied Research, Turner Fairbank Highway Research Center, McLean, VA. Available at *http://www.tfhrc.gov/library/UVA/introset.htm*.

NOAH (1999). Available at *http://www.albinism.org/*.

Olson, P. L. (1985). "A survey of the condition of lighting equipment on vehicles in the United States." SAE Technical Paper Series #850229, Society of Automotive Engineers, Warrendale, PA., pp. 1–14.

Olson, P. L. and Sivak, M. (1984a). “Glare from automobile rear-vision mirrors.” Human Factors 26, 269–282.

Olson, P. L. and Sivak, M. (1984b). “Glare and headlighting design.” Report No. 840047, Society of Automotive Engineers, Warrendale, PA., pp. 1-9.

Owens, D. A. and Sivak, M. (1996). “Differentiation of visibility and alcohol as contributors to twilight road fatalities.” *Human Factors* **38**, 680–689, page 20 under ‘Effect of Glare on Accident Frequency.’

Owsley, C, Sloane, M. E., Stalvey, B, and Wells, J. ([YEAR?]). “Older drivers and cataract: driving habits and crash risk.” *Journals of Gerontology A: Biological and Medical Sciences*. **54**, 203–211.

Peet, J. S. and Neuzil, D. (1972). “Independent versus narrow-median alignment: Comparative economy, safety, and aesthetics.” *Highway Research Record 390*, National Research Council, Transportation Research Board, Washington, DC, pp. 1–14.

Pitts, D. G. (1990). “Ultraviolet-absorbing spectacle lenses, contact lenses, and intraocular lenses.” *Optometry and Vision Science*, **67**, 435–440.

Powers, L. D. and Solomon, D. (1965). “Headlight glare and median width—Three exploratory studies.” *Public Roads*, **33**(7), 125–242.

Pulling, N. H., Wolf, E., Sturgis, S. P., Vaillancourt, D. R., and Dolliver, J .J. (1980). “Headlight glare resistance and driver age.” *Human Factors*, **22**, 103–112.

Rea, M. (1990). “Essay by invitation.” *LD&A*, October.

Rog, S. J., White, C. W., and Williams, T. T. (1986). “Ultraviolet effects on visual acuity in pseudophakia.” *American Journal of Optometry and Physiological Optics*, **63**, 867–872.

Rösenhahn, E. O. (1999). “Headlamp components for adaptive frontlighting—Usability of a lighting function for adverse weather conditions.” *Progress in Automobile Lighting, Department of Lighting Technology. Proceedings of the Conference*, pp. 677–688.

RP-8 (2000). American National Standard Practice for Roadway Lighting, *ANSI/IESNA RP-8-00* (ISBN#0-87995-160-5), pp. 1–61. The Standard Practice Subcommittee of the IESNA Roadway Lighting Committee, 120 Wall Street, New York, NY 10005.

Russell, E. R., Rys, M., Rys, A., and Keck, M. (1999). “Characteristics and needs for overhead guide sign illumination from vehicular headlamps.” Report No. FHWA-RD-98-135, Kansas State University Department of Civil Engineering, pp. 1–146.

SAE Draft Technical Report (1996). “Recommendations of the SAE task force on headlamp mounting height, SAE J 2338.” *SAE Ground Vehicle Lighting Standards Manual*, 2001 Edition, Society of Automotive Engineers, Warrendale, PA, pp. 113-116.

San Francisco Chronicle (June 28, 1999). “Bright headlights A glaring problem on roadways.”

Schieber, F. (1986). “Vision assessment technology and screening older drivers: past practices and emerging techniques.” *Transportation in an Aging Society*, pp. 325–378. Special Report 218, Committee for the study on Improving Mobility and Safety for Older Persons, Transportation Research Board, Washington, DC.

Schiflett, S. G., Cadena, D.G., and Hemion, R. H. (1969). “Headlight glare effects on driver fatigue. Report on Phase II of a Study for U.S. Bureau of Public Roads.” Southwest Research Institute, San Antonio, TX.

Schmidt-Clausen, H. J. and Bindels, J. T. H. (1974). “Assessment of discomfort glare in motor vehicle lighting.” *Lighting Research and Technology,* **6**(2), 79–88.

Schoon, C. C. and Schreuder, D. A. (1993). “HID car headlights and road safety.” SWOV Institute for Road Safety Research, pp. 1–33. SWOV Institute for Road Safety Research, Leidschendam, The Netherlands.

Schwab, R. N. (2000). Personnal communication, October 2000.

Schwab, R. N. and Hemion, R. H. (1971). “ Improvement of visibility for night driving.” HRR No. 377, Visibility 11 Report, pp. 1-18. Transportation Research Board, Washington DC.

Schwab, R. N., Solomon, D., and Lyons, J. F. (1972). “Monetary value drivers place on comfort in night driving.” Report No. FHWA-RD-72-14, Environmental Design and Control Division, U.S. Department of Transportation, Federal Highway Administration, Washington, DC pp. 1–28.

Sivak, M. (1996). “The information that drivers use: Is it indeed 90% visual?” Perception 25, 1081–1089.

Sivak, M., Flannagan, M. J., Budnik, E. A., Flannagan, E. C., and Kojima, S. (1997). “The location of headlamps and driver eye positions in vehicles sold in the USA.” *Ergonomics*, **40**, 872–878.

Sivak, M., Flannagan, M., Ensing, M., and Simmons, C. J. (1991) “Discomfort glare is task dependent.” *International Journal of Vehicle Design*, **12**(2), 152-159.

Sivak, M., Flannagan, M., and Gellatly, A. W. (1993). “Influence of truck driver eye position on effectiveness of retroreflective traffic signs.” *Lighting Research Technology,* **25**, 31-36.

Sivak, M., Flannagan, M. J., and Sato, T. (1993). “The relative importance of horizontal and vertical aim of low-beam headlamps.” Report No. UMTRI-93-26 University of Michigan Transportation Research Institute, Ann Arbor, MI, pp. 1–36.

Sivak, M., Flannagan, M. J., Traube, E. C., Aoki, M., and Sayer, J. R. (1994). “Evaluation of an active headlight system.” Report No. UMTRI-94-17, University of Michigan Transportation Research Institute, pp. 1–30.

Sivak, M., Flannagan, M. J., Traube, E. C., and Kojima, S. (1999). “The influence of stimulus duration on discomfort glare for persons with and without visual correction.” *Transportation Human Factors*, **1**, 147–158.

Sivak, M., Flannagan, M. J., Traube, E. C., Kojima, S. (1997). “The influence of stimulus duration on discomfort glare for persons with and without visual correction.” Report No. UMTRI-97-23, University of Michigan Transportation Research Institute.

Sivak, M., Helmers, G., Owens, D.A., Flannagan, M. (1992). Evaluation of proposed low-beam head-lighting patterns. University of Michigan Transportation Research Institute, Ann Arbor. Sponsored by the Motor Vehicle Manufacturers Association, Detroit, MI. Report No. UMTRI-92-14.

Sivak, M., Olson, P. L., and Zeltner, K. A. (1989). “Effect of prior headlighting experience on ratings of discomfort glare.” *Human Factors,* **31**, 391– 395.

Sivak, M., Simmons, C. J., and Flannagan, M. (1990). “Effect of headlamp area on discomfort glare.” *Lighting Research Technology,* **22**, 49–52.

Sliney, D. H., et al. (1984). *Ultraviolet Countermeasures*.

Sliney, D. H., Fast, P., and Ricksand, A. (1994). “Analysis of potential health hazards of ultraviolet headlamps.” Presented at the Transportation Research Board 73rd Annual Meeting, Washington, DC.

Smart, A. E. (1970). “An investigation of chromatic glare with particular reference to night driving.” *Lighting Research and Technology,* **2**, 33–37.

Stark, W. J., Whitney, C. E., Chandler, J. W., and Worthen, D. M. (1986). “Trends in intraocular lens implantation in the United States.” *Archives of Ophthalmology,* **104**, 1769–1770.

Steinert, R. F. (1997). “Consultation section: cataract surgical problem.” *Journal of Cataract and Refractive Surgery,* **23**. Available at *http://www.ascrs.org/publications/jcrs/ccsoct7.htm1#steinert.*

Stiles, W. S. (1928–29). “The effect of glare on the brightness difference threshold.” *Proceedings of the Royal Society (London)* **B104**, 322.

Sullivan, J. M. and Flannagan, M. J. (2001). “Visual effects of blue-tinted tungsten-halogen headlamp bulbs.” Report No. UMTRI-2001-9, University of Michigan Transportation Research Institute, pp. 1–24.

Telford, E. T. and Israel, R.J. (1953). “Median study (California).” *Proceedings of the 32nd Annual Meeting,* Highway Research Board, pp. 208–231.

Theeuwes, J. and Alferdiock, J. W. A. M. (1996). “The relation between discomfort glare and driving behavior.” Report No. DOT HS 808 452, U.S. Department of Transportation, National Highway Traffic Safety Administration, Washington, DC, pp. 1–64.

Transportation Research Board, 1988. “Transportation in an aging society. Improving mobility and safety for older persons.” Special Report 218, Volume 2, chapter on headlamp performance factors affecting the visibility of older drivers in night driving. National Research Council, Transportation Research Board, pp. 379–403.

Ucke, C. (1973). *Streulicht im Auge* (Stray light in the eye). Ph.D. thesis, University of Munich, October 1973, Germany.

Ultralux (1994). Ultralux AB brochure, Swedish National Road Administration.

USHHS (1994). U.S. Department of Health and Human Services, personal communication, February, 1994.

USHHS (2001). U.S. Department of Health and Human Services, personal communication, May, 2001.

Vos, J. J. and Padmos, P. (1983). “Stray light, contrast sensitivity and the critical object in relation to tunnel entrance lighting.” DIE transactions of the International Commission on Illumination, 20th session.

Wald, G. (1945). “Human vision and the spectrum.” *Science* **101**, 653–658.

Werner, J. S. and Hardenbergh, F. E. (1983). “Spectral sensitivity of the pseudophakic eye.” *Archives of Ophthalmology*, **101**, 758–760.

Weston. H. C. (1954). “Visual fatigue.” *Illuminating Engineering*, **49**, 63–76. Also in *Selected Papers on Architectural Lighting*, M. S. Rea, ed. (1992), pp. 286–297.

White, C. W. and Wolbarsht, M. L. (1975). “Color vision in the ultraviolet” (abstract). *Journal of the Optical Society of America*, **65**, 1119.

Winter, D. J. (1985). “Learning and motivational characteristics of older people pertaining to traffic safety.” 55+, 77–85.

Wörner, B. (1999). “Adaptive frontlighting—Experimental system development and functional evaluation.” Progress in Automobile Lighting, Department of Lighting Technology, Proceedings of the Conference.

Zigman, S. (1983). “Effects of near ultraviolet radiation on the lens and retina.” *Documenta Ophthalmologica*, **55**, 375–391.