NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION

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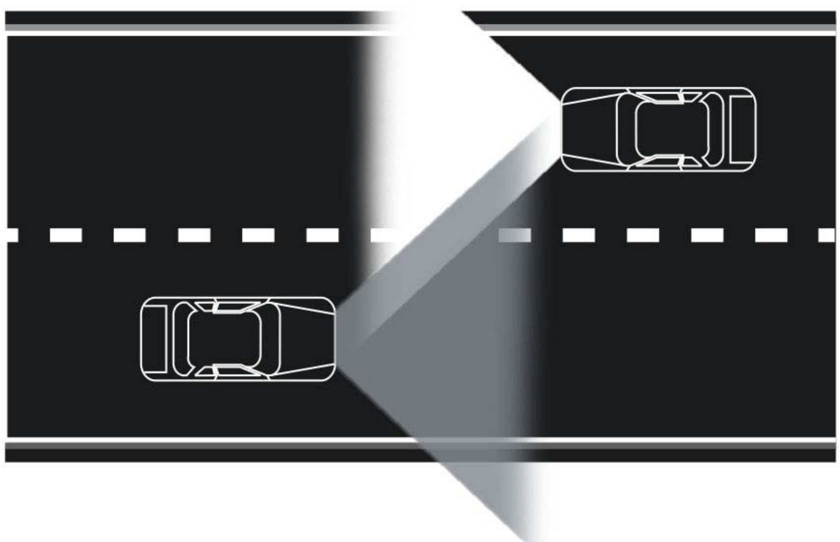
NIGHTTIME GLARE
AND DRIVING PERFORMANCE



REPORT TO CONGRESS

February, 2007

EXECUTIVE SUMMARY

Direction from Congress

As part of the "Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users" (SAFETEA-LU), Congress directed the U.S. Department of Transportation to conduct a study on the risks associated with glare to oncoming vehicles.

Specifically, Section 2015 of SAFETEA-LU provides that the study examine "the risks associated with glare to oncoming drivers, including increased risks to drivers on two-lane highways, increased risks to drivers over the age of 50, and the overall effects of glare on driver performance." The same section requires that a report be submitted not later than 18 months after the date of enactment of the Act, and that the report should contain the "results of the study and any recommendations regarding measures to reduce the risks associated with glare to oncoming drivers." The National Highway Traffic Safety Administration (NHTSA) has prepared this preliminary report in response to this Congressional direction.

In order to address the various issues that relate headlamp glare to driver performance and risk, NHTSA has initiated a study including the following tasks:

- Analyses to compare the relative effects of different headlamp characteristics, such as mounting height, light source type, aim and beam intensity patterns, on visibility and glare to oncoming drivers along two-lane roadways.
- Assessment of headlamp aim characteristics on a representative sample of vehicles.
- A field experiment to study visual performance of older drivers following exposure to glare light.

- Development and evaluation of a prototype adaptive headlamp system with the potential to reduce glare while maintaining visibility by automatically decreasing the level of light intensity when other vehicles are nearby.

All of the tasks in this study will be completed by March 10, 2008, after the February 10, 2007, due date established for the report to Congress. To fulfill this requirement, the present interim report provides information on glare that is currently available. At the conclusion of the ongoing research activity, a comprehensive research report will be available to document each of the activities above and to supplement the information contained in this report.

Characterizing Glare

Glare is a sensation caused by bright light in one's field of view. Glare can reduce one's ability to see, create feelings of discomfort or both. The term *headlamp glare* is defined herewith as visibility reductions or discomfort caused by viewing oncoming vehicle headlamps or headlamps in rear view mirrors.

Glare reduces seeing distance because it causes light scatter in the eyes, which in turn reduces the contrast of roadway objects. This effect is known as "disability glare." The greater the intensity of the glare light and the closer the glare light is to where one is looking, the greater the disability glare will be. Disability glare can lead to the following effects:

- <u>Decreasing visibility distance</u>. The distance at which an object can be seen is known as the "visibility distance." This distance is reduced when disability glare is present.
- <u>Increasing reaction times</u>. As the intensity of oncoming headlamps increases, drivers' reaction times to objects in and along the roadway become longer.
- <u>Increasing recovery time</u>. After drivers pass an oncoming vehicle, the glare has a lasting effect that increases the time it takes for the drivers' eyes to recover their ability to detect objects. During that time, the visibility distance is reduced and reaction times are increased.

As described above, headlamps can produce a sensation termed "discomfort glare." This is the feeling of annoyance or even pain that is possible when viewing a bright light. Experiencing discomfort can distract drivers from the driving task, cause them to slow down, and cause drift slightly in their lane.

Possible Factors Contributing to Glare

Vehicle headlamps are necessary for sufficient nighttime visibility and safety, and headlamp glare has long been recognized as a potential problem. However, concerns from the public about nighttime glare have increased in recent years. A public comment docket regarding headlamp glare opened in 2001 and has received more than 5700 comments to date, making it one of NHTSA's most active dockets.

Several factors associated with recent vehicle and lighting developments may explain the driving public's passion regarding nighttime glare. These include increasing light intensity levels, headlamp mounting height on larger vehicles, novel headlamp color appearance (specifically the bluish appearance of some headlamps), smaller headlamp size, variations in headlamp aim on the U.S. vehicle fleet, and an increase in the presence of auxiliary lighting, such as fog lamps. The increasing age of the driving public may be another factor. Since all of these factors have changed in parallel, assigning the cause of these concerns to any single factor is difficult.

This report presents information on each of the questions raised by Congress in SAFETEA-LU, Section 2015, regarding the effect of glare on driving performance and crash risk.

Visibility and Glare – A Tradeoff

With low beam headlamps, there is a tradeoff between visibility and glare, because the illumination from headlamps that contribute to visibility for one driver can make them more troublesome with respect to glare for another. Present regulations for low beams require them to produce sufficient light levels in locations that contribute to forward visibility, but limit the light levels they produce in locations where they would contribute to glare to other drivers. Because these two locations are sometimes the same due the varying geometry of roadways, the illumination desired for detecting road hazards needs to be limited to minimize the adverse effects on other drivers.

Associating Glare with Driving Performance and Crash Risk

While greater seeing distance and shorter reaction times have an intuitive connection to safety, it is very difficult to directly relate crash risk to nighttime glare. In part, this is due to the multiple driver, vehicle, and environmental factors that contribute to a crash. It is also due to the difficulty that crash investigators have in determining the role of glare and low visibility in crashes. However, nighttime glare cannot be ruled out as a causal factor in crashes. In addition to influencing safety, glare may cause some drivers, particularly older drivers, to restrict their nighttime driving.

What can be shown is a definitive relationship between important aspects of driving performance and glare. For example, surrogate measures such as reduced visibility are used to relate lighting conditions to increased risk. Looking away from the roadway scene, or from rear view mirrors in the presence of glare, might also logically constitute an increase in crash risk. These measures are typical of those used in laboratory, test track, and on-road research to evaluate the effects of headlamp illumination on driver safety.

Nighttime Glare and Increased Risks to Drivers on Two-Lane Highways

Two-lane highways, as compared to multi-lane roadways and expressways, may present the "worst-case" scenario for nighttime glare. The reasons for this include:

- <u>Lower light levels</u>. Nighttime glare on unlighted roadways is more problematic because the visibility of an object is influenced by the overall light level. Since light levels tend to be lower on two-lane highways, objects along these roads are less visible in the presence of glare. In addition to the reduced visibility, the lower light levels on two lane highways increases discomfort glare because the relative brightness difference between headlamps and the roadway background is higher on these roads.

- <u>Oncoming traffic closer to driver's line of sight.</u> Because of the closer proximity of oncoming glare on two lane roadways, the beam pattern is directing more light at oncoming drivers, which produces more scattered light in their eyes.
- <u>Complex roadway geometry.</u> Two-lane highways often have complicated roadway geometries, including sharper curves and steeper grades. Thus, drivers on two lane roadways may be exposed to a higher range of oncoming headlamp glare than on multi-lane roadways.
- <u>Less restricted roadway access</u>. The greater potential for hazards to be found in any number of locations along the roadway increases the complexity of the driving task and makes glare more problematic and arguably less safe than it would be under easier driving situations.
- <u>Fewer roadway markings</u>. Roadway markings in and of themselves have no direct impact on the amount of light that oncoming headlamps produce toward a driver's eyes. However, they make the driving task easier by providing visual guidance about the geometry of the roadways and other roadway conditions.
- <u>Closer proximity of pedestrians</u>. Pedestrians are not always easily seen. While they may not be found frequently along two-lane roadways, they are in closer proximity when they are encountered on these kinds of roads. The difficulty seeing them at night can increase the difficulty of nighttime driving, and therefore, increase the impact of glare on both visibility and comfort.

Nighttime Glare and Increased Risks for Older Drivers

The visual system changes as people age, resulting in differences that are important in the context of nighttime driving and headlamp glare. These differences can be categorized as optical and neurological.

As people age, less light enters the eye due to smaller pupils and thicker, less transparent optical media. This latter effect results in more scattered light in the presence of a glare light for older drivers. This increased scatter results in lower perceived contrast of a potential hazard against its background for an older driver than for a younger one. Older drivers also take longer for their eyes to recover their sensitivity after being exposed to glare.

The three major retinal neurological problems associated with aging are macular degeneration, diabetic retinopathy, and detached retina. Glare is particularly problematic for older drivers who have one or more of these neural anomalies, even in early stages of disease development.

Factors That Contribute to Glare and Crash Risk and Changes in Driving Performance

The following design and operational factors are considered as they affect glare and associated risks.

- Headlamp mounting height. Higher mounting heights may produce improved visibility for drivers but could also result in higher light levels at the eyes of oncoming drivers, increasing their disability and discomfort glare.
- Lamp aim. Improperly aimed headlamps can increase glare and cause objects to remain invisible to oncoming drivers for longer durations. This effect is intensified when headlamps with higher mounting heights are improperly aimed. Improper headlamp aim can also reduce visibility for a driver.

- <u>Headlamp beam distribution</u>. Headlamps are optically designed to direct different intensities of light towards different directions. Federal regulations set minimum and maximum intensity levels that provide some control of the beam pattern to limit glare and provide light for seeing the roadway environment. Some locations within headlamp beams are not regulated in terms of allowable light levels. If headlamps produce high light levels in these locations, oncoming drivers might experience glare.
- <u>Headlamp color</u>. Research indicates that people experience more discomfort when exposed to "bluer" high intensity discharge headlamps than when they are exposed to "yellower" halogen headlamps (halogen headlamps are found on most vehicles in the United States). Thus, color can affect discomfort glare. No evidence exists to link the oncoming headlamp color to visibility reductions.
- <u>Headlamp size</u>. While lamps of different sizes are statistically equal when seen from far away, smaller lamps might be more uncomfortable at closer distances.
- <u>Headlamps and windshield cleanliness and condition</u>. Headlamps that are dirty or damaged can produce higher light levels to oncoming drivers and also produce lower light levels on the roadway, reducing forward visibility for drivers who have dirty or damaged headlamps. Windshields that are soiled or damaged can scatter light and potentially increase the effects of glare.

Table 1 in the main body of the present report describes potential glare countermeasures, many of which are included in the current research program.

Next Steps

This report is an initial step in responding to the Congressional requirement contained in Section 2015 of SAFETEA-LU. The study authorized in that section is still ongoing, and when the full study is completed, it will be published as a final NHTSA technical report.

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1. PURPOSE

On August 10, 2005, President George W. Bush signed the bill passed by the U.S. Congress entitled the "Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users" (SAFETEA-LU).[1] * The law authorizes the federal government's ground transportation programs administered by the U.S. Department of Transportation. The text of that Act included the following language:

> *SEC. 2015. DRIVER PERFORMANCE STUDY.*
> *(a) In General.--Using funds made available to carry out section 403 of title 23, United States Code, for fiscal year 2005, the Secretary shall make $1,000,000 available to conduct a study on the risks associated with glare to oncoming drivers, including increased risks to drivers on 2-lane highways, increased risks to drivers over the age of 50, and the overall effects of glare on driver performance.*
> *(b) Report.--Not later than 18 months after the date of enactment of this Act, the Secretary shall transmit to the Committee on Transportation and Infrastructure of the House of Representatives and the Committee on Commerce, Science, and Transportation of the Senate a report on the results of the study and any recommendations regarding measures to reduce the risks associated with glare to oncoming drivers.*

In order to address the various issues that relate headlamp glare to driver performance and risk, NHTSA has initiated a study including the following tasks:

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[1] U.S. Congress. 2005. *Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users.* Washington, DC: U.S. Government Printing Office.

* Reference numbers cited are repeated wherever applicable

- Analyses to compare the relative effects of different headlamp characteristics, such as mounting height, light source type, aim and beam intensity patterns, on visibility and glare to oncoming drivers along two-lane roadways.
- Assessment of headlamp aim characteristics on a representative sample of vehicles.
- A field experiment to study visual performance of older drivers following exposure to glare light.
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All of the tasks in this study will be completed by March 10, 2008, after the February 10, 2007, due date established for the report to Congress. To fulfill this requirement, the present interim report provides information on glare that is currently available. At the conclusion of the ongoing research activity, a comprehensive research report will be available to document each of the activities above and to supplement the information contained in this report.

As the relevant agency within the U.S. Department of Transportation to undertake the study authorized above, the National Highway Traffic Safety Administration (NHTSA) hereby submits the present report as a summary of its efforts to understand the issue of headlamp glare and to address the instructions provided by Congress in SAFETEA-LU to study the "risks associated with glare to oncoming drivers, including increased risks to drivers on two-lane highways, increased risks to drivers over the age of 50, and the overall effects of glare on driver performance."

2. WHAT ARE THE BASIC ISSUES RELATED TO HEADLAMP GLARE?

In this section, glare is defined and the role and purpose of vehicle headlamps is discussed, including why drivers need headlamps and the specific ways that headlamps fill that need.

What is glare?

> *Glare is a sensation in response to light that can take a number of forms.*

Glare is defined as a "harsh uncomfortably bright light."[2] Glare is a sensation in response to light that can take a number of forms. Although light is necessary for vision, light - usually bright light - can also reduce visibility of objects in the field of view enough to make some objects invisible. As this report will describe, bright light can create *scatter* inside the eye not unlike that experienced when looking through fogged glass or smoke, which makes objects harder to see. Light that is much brighter than the rest of one's field of view can also cause discomfort, annoyance, or even pain, and this sensation is another form of glare. When driving, glare can be caused by bright lights seen against a dark background, such as when headlamps of oncoming vehicles are seen in the field of view (or when following vehicles are seen in mirrors); glare can also be caused by a very bright foreground, such as a bright, clear sky that "washes-out" visibility of dashboard instruments while driving; or, glare can be caused by light reflected by fog or snow that makes objects harder to see. This report discusses *headlamp glare* from oncoming and following vehicles, its effects on nighttime visibility and its possible impact on crash risk.

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[2] Merriam Webster Dictionary. Retrieved December 14, 2006 from www.merriamwebster.com.

What is the basic problem with headlamp glare?

With vehicle headlamps, there is often a tradeoff between *visibility* and *glare* such that the characteristics of headlamps that contribute to visibility for one driver are often the same that make them more troublesome with respect to glare for another.

To be of optimal use, vehicle headlamps must provide sufficient lighting far enough ahead in the field of view to allow a driver to respond to a hazard while minimizing the amount of light facing oncoming traffic; see Figure 1. In terms of the four regions shown in this figure, headlamp beam patterns generally minimize light in the quadrant corresponding to potential glare for oncoming drivers, while producing sufficient light in the other quadrants to aid in forward and peripheral visibility. Of course, the boundaries between regions where light is likely to aid in forward visibility and regions where light can result in potential glare vary between situations and individuals. Changes in road curvature and in the locations of oncoming vehicles may happen so that light in any region could enhance visibility of potential hazards or could create glare. Responding to a hazard in a timely manner requires seeing it at distances of hundreds of feet at most typical driving speeds.[3] To make objects hundreds of feet away visible, vehicle headlamps need to produce and project high light levels, particularly in the quadrant labeled "forward visibility" in Figure 1.

[3] Olson PL, Cleveland DE, Fancher PS, Kostyniuk LP, Schneider LW. 1984. *NCHRP Report 270: Parameters Affecting Stopping Sight Distance*. Washington, DC: National Cooperative Highway Research Program.

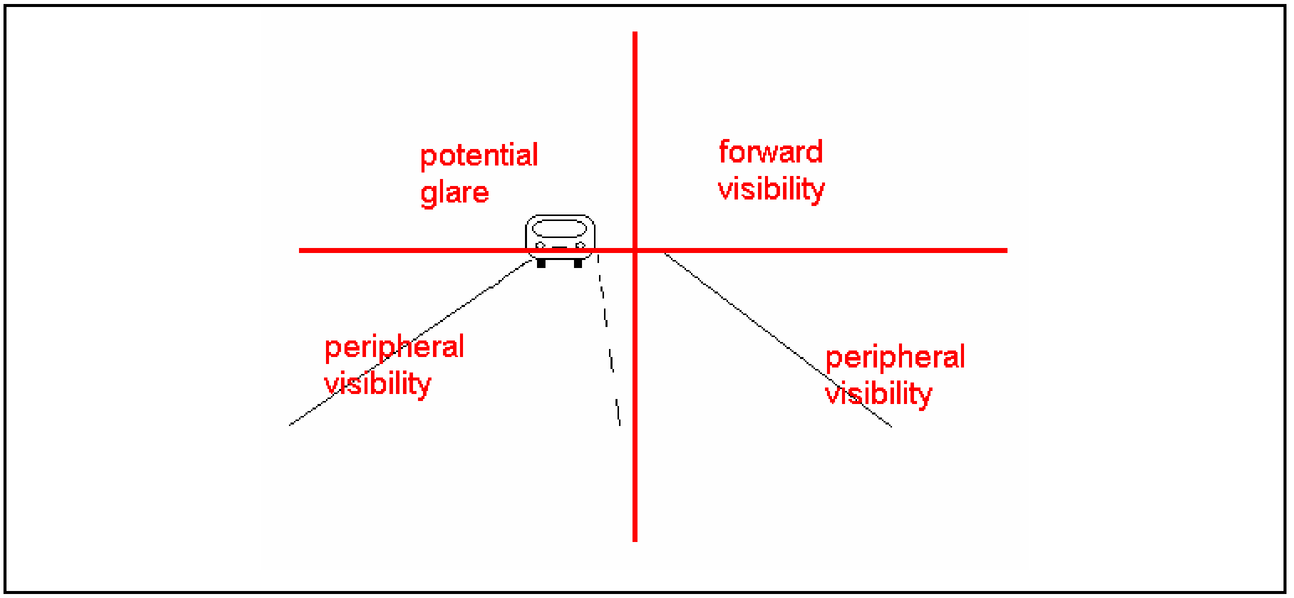

Figure 1. Regions where one's own headlamps are likely to contribute to visibility and to glare to oncoming drivers.

Vehicles are equipped with two beam patterns, typically denoted the *low beam* and the *high beam*. The high beam pattern is designed to produce high light levels in both upper regions of Figure 1; because this pattern would create unacceptable glare to oncoming drivers, the high beam is generally not used when oncoming vehicles are present. In fact, most drivers use the low beam most of the time, even when the high beam would be more appropriate for forward visibility.[4]

Because the size of a headlamp is generally restricted by the size of the vehicles and important aerodynamic factors that influence a vehicle's fuel efficiency,[5] headlamps are generally small and

[4] Sullivan JM, Adachi G, Mefford ML, Flannagan MJ. 2004. High-beam headlamp usage on unlighted rural roadways. *Lighting Research and Technology* 36(1): 59-67.

[5] Environmental Defense. 1999. *Green Cars: A Guide to Cleaner Vehicle Production, Use and Disposal.* New York, NY: Environmental Defense.

very bright. Discomfort from bright headlamps may cause some people to reduce the time they spend driving at night, particularly as they get older.[6]

What is the purpose of headlamps?

Vehicle headlamps illuminate the area ahead of a vehicle, including overhead signs. They also make the vehicle itself visible to other road users. Headlamps are an essential part of the roadway visibility system, as most of the U.S. highway system is not equipped with fixed, pole-mounted lighting systems[7] and nighttime driving is an essential activity in today's economy.[8] An assumption in standards that contain provisions for lighting on vehicles and along roadways is that lighting contributes to improved visibility, which in turn can help reduce the likelihood of crashes.

It is often difficult to link headlamp glare to driving safety.

Isolating the effects of lighting on visibility and therefore driving safety at night is difficult because of many confounding variables. For example, nighttime drivers are more likely to be tired or intoxicated[9] than daytime drivers, making the impact of reduced visibility difficult to extract.

Some data do support the role of light in improving visibility and therefore driving safety. One study used the change in daylight levels at the same clock time on successive weeks following

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[6] Brabyn JA, Schneck ME, Lott LA, Haegerstrom-Portnöy G. 2005. Night driving self restriction: Vision function and gender differences. *Optometry and Vision Science* 82: 755-764.

[7] Chaudhary NK, Geary LL, Preusser DF, Cosgrove LA. 2005. *Connecticut's Day and Night Safety Belt Use*, DOT HS 809 954. Washington, DC: National Highway Traffic Safety Administration.

[8] Pitchford P, Fisher M. 2006. Steering trucks to a night shift. *Riverside [CA] Press-Enterprise* (5 August).

[9] National Highway Traffic Safety Administration. 2005. *Traffic Safety Facts 2004.* Washington, DC: National Highway Traffic Safety Administration.

the transitions to and from daylight savings time.[10] The authors assumed that the driving populations were the same at the same clock time before and after the start or end of daylight savings time, so drivers were presumed to be statistically identical with respect to confounding factors like tiredness or intoxication. Assuming this is correct, then the only consistent difference in conditions before and after daylight savings time was the difference in visibility due to daylight level (light or dark). The authors found a significant reduction in fatal pedestrian crashes under daylight level relative to darkness. However, this reduction did not occur for all crash types. Single-vehicle, run-off-the-road crashes were not affected by light or darkness, for example. This study does provide some evidence that good visibility has important safety implications for some types of crashes. Therefore, by extrapolation, one can infer that light, either from the vehicle or on nearby poles, would support visibility and thus, safety.

What is different between headlamps on today's vehicles and earlier ones?

Headlamps look different today than in previous years.

New headlamp technologies are changing the appearance of oncoming vehicles at night on U.S. roadways in several important ways. Newly developed headlamps, using *high intensity discharge* (HID) light sources produce more light and appear "bluer" than conventional headlamps, and are becoming more common.[11] Headlamps that produce more light than earlier ones, but conform to the same standards, can result in beam patterns that differ greatly from earlier headlamps, particularly in locations that are not regulated to produce minimum or maximum light levels. These patterns often result in wider and brighter distributions of light on and along the roadway. In addition to their different light distributions, HID headlamps last longer than conventional halogen

[10] Sullivan J, Flannagan M. 2002. The role of ambient light level in fatal crashes: Inferences from daylight saving time transitions. *Accident Analysis and Prevention* 34: 487-498.

[11] Jost K. 1995. Anatomy of high-intensity discharge headlamps. *Automotive Engineering* (November): 38.

headlamps, often for the life of the vehicle, making them attractive from a maintenance perspective.

The lighted areas of some headlamps are smaller in size, which increases their brightness.[12] For example, a tubular fluorescent lamp might produce the same amount of light as a clear incandescent light bulb, but because the filament of the light bulb is much smaller than the surface of the fluorescent tube, the filament is much brighter in appearance. Additionally, vehicles themselves have been increasing in height,[13] resulting in higher mounting heights for headlamps. This can be problematic because the headlamps' patterns of light might not account for the increased mounting height, and therefore will project a bright part of the beam to the oncoming driver. [14] These brighter headlamps might be persistently present in rear view mirrors from vehicles located behind a driver for a long period of time. Brighter headlamps with different beam distributions can reduce visibility of objects along the road by increasing the *amount* and *duration* of light reaching an oncoming driver's eyes.[15] These factors and others such as the color of light can also increase drivers' perception of discomfort from glare.

Another factor that can influence glare, which has been changing in recent decades, is headlamp aim. Headlamps are designed to meet a stringent set of luminous intensity values at several angles and locations specified by the U.S. Federal Government,[16] but factors such as vehicle age,

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[12] Rea MS (ed.). 2000. *IESNA Lighting Handbook: Reference and Application*, 9th ed. New York, NY: Illuminating Engineering Society of North America.

[13] White MJ. 2004. The "arms race" on American roads: The effect of sport utility vehicles and pickup trucks on traffic safety. *Journal of Law and Economics* 47: 333-355.

[14] Society of Automotive Engineers. 1999. Performance requirements for motor vehicle headlamps, SAE J1383. In *Ground Vehicle Lighting Standards Manual,* HS-34. Warrendale, PA: Society of Automotive Engineers.

[15] Chen J. 2004. *Effects of Headlamp Glare Exposure on Glare Recovery and Discomfort* [M.S. thesis]. Troy, NY: Rensselaer Polytechnic Institute.

[16] U.S. Congress. 2004. *Federal Motor Vehicle Safety Standards, No. 108: Lamps, Reflective Devices, and Associated Equipment.* Washington, DC: U.S. Government Printing Office.

road conditions, loading and damage to the vehicle can contribute to poorly aimed headlamps, even if the headlamps themselves produce the correct distributions of light. Some states have no requirements that headlamps be properly aimed at regular intervals. A recent NHTSA-sponsored survey of headlamp aim in New York State[17] found that two-thirds of passenger cars measured had at least one headlamp improperly aimed either upward or downward. When headlamps are improperly aimed upward, they can produce higher luminous intensity values toward oncoming vehicles than properly aimed headlamps, according to another NHTSA-sponsored study.[18] When they are aimed downward, they can result in reduced forward visibility for the driver.

How does headlamp glare affect the driving public?

In 2001, NHTSA solicited comments from the driving public, the automotive lighting industry, and advocates for driving safety regarding the causes and importance of headlamp glare.[19] A public comment docket opened in 2001 has received more than 5700 comments to date, making it one of NHTSA's most active dockets. Many of the comments NHTSA received from the driving public state that headlamp glare is an important problem. NHTSA has also surveyed members of the U.S. driving public to better understand complaints regarding headlamp glare.[20] Some comments state that "blue" headlamps are more uncomfortable when viewed from

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[17] Lighting Research Center, Rensselaer Polytechnic Institute. 2005. *Assessment of Headlamp Glare and Potential Countermeasures: New Methodology for the Assessment of Headlamp Aim* [report submitted to NHTSA]. Troy, NY: Rensselaer Polytechnic Institute.

[18] Van Derlofske J, Chen J, Bullough JD, Akashi Y. 2006. Headlamp glare exposure and recovery (SAE paper 2005-01-1573). *Society of Automotive Engineers 2005 Transactions Journal of Passenger Cars - Mechanical Systems* 114(6): 1974-1981.

[19] National Highway Traffic Safety Administration. 2001. *Glare From Headlamps and Other Front Mounted Lamps* [Docket No. 01-8885]. Washington, DC: U.S. Government Printing Office.

[20] Singh S, Perel M. 2004. *Drivers' Perceptions of Headlamp Glare from Oncoming and Following Vehicles*, DOT HS 809 669. Washington, DC: National Highway Traffic Safety Administration.

oncoming vehicles while driving, and some focus on auxiliary lighting such as fog lamps.[21] Many comments also address the higher mounting heights of headlamps, which can result in increased light levels at oncoming drivers' eyes. As mentioned above, many factors have changed simultaneously regarding headlamp light sources and locations; this makes assigning the cause of complaints to any single factor difficult.

In order to address the directions from the U.S. Congress to study the effects of headlamp glare on driving performance and the risks associated with headlamp glare, NHTSA has undertaken research and reviewed previously published research on the combined effects of headlamp color, size, beam pattern characteristics, and mounting characteristics on visual performance and on visual comfort for drivers using and facing headlamps. The present report summarizes NHTSA's findings to date; technical reports will be released at the conclusion of each project.

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[21] Sivak M, Flannagan MJ, Traube EC, Hashimoto H, Kojima S. 1996. *Fog Lamps: Frequency of Installation and Nature of Use*, UMTRI-96-31. Ann Arbor, MI: University of Michigan.

3. WHAT ARE THE EFFECTS OF GLARE ON DRIVER PERFORMANCE?

Headlamp glare cannot be ruled out as a factor in driving safety.

An important issue to remember in discussing the effects of glare on driver performance is that evidence linking headlamp glare and crash risk is difficult to obtain. A survey of crash reports from several U.S. states conducted several decades ago found that the percentage of accidents that could be at least partly related to headlamp glare was no more than 1%.[22] A recent in-house NHTSA evaluation shows that an average of 0.3% of nighttime fatal crashes list glare as a contributing factor. Assigning a specific percentage of crashes to glare is difficult when considering that potentially at-fault drivers might claim in police reports that they were impaired by glare in attempts to seem less liable. There could also be crashes for which glare was a factor, but which were unreported. Thus, headlamp glare cannot be ruled out as a factor in driving safety. Glare might also affect the probability of driving at all. Older drivers, for example, sometimes report headlamp glare as a cause for refraining from nighttime driving.[6]

This report summarizes what is known about the links in the logical chain from headlamp glare to reduced safety. As discussed in this section, headlamp glare can and does have measurable impacts on visibility, and may have other behavioral impacts. Logically, visibility is an important factor in determining safety,[10] and much of the research on glare and safety has used visibility (in terms of distance at which potential hazards can be seen, and of how quickly and accurately they can be seen) as a surrogate for safety.

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[22] Hemion RH. 1969. *A Preliminary Cost-Benefit Study of Headlamp Glare Reduction*, AR-683. San Antonio, TX: Southwest Research Institute.

Several types of experiments and research studies on glare and driving performance are discussed: *simulation* or *calculation analysis studies*, in which effects of glare are predicted using software or other tools rather than directly measured with human subjects; *laboratory studies*, in which the experiments are controlled carefully but often do not capture all of the realistic conditions directly applicable to driving;[18,23] *field studies*, which are usually conducted outdoors along mocked-up conditions similar to those along actual roadways;[24,25] and *naturalistic studies*, which are not really experiments, but involve monitoring people driving in conditions as close to the "real world" as possible.[26]

How does glare reduce visibility?

Glare from vehicle headlamps has several effects. Not surprisingly, glare reduces visibility, not only while the glare light is visible, but even after the glare light is no longer in the field of view, that is, after an oncoming vehicle has passed by. These two effects are discussed later in this report.

Headlamp glare causes light scatter in the eyes, which makes objects less visible.

The eye's lens and cornea are not perfectly clear,[12] and the center of the eye contains a liquid that accumulates debris from dead cells in the eye.[12] As a result, all light entering the eye is

[23] Flannagan MJ. 1999. *Subjective and Objective Aspects of Headlamp Glare: Effects of Size and Spectral Power Distribution*, UMTRI-99-36. Ann Arbor, MI: University of Michigan.

[24] Bullough JD, Van Derlofske J, Dee P, Chen J, Akashi Y. 2003. *An Investigation of Headlamp Glare: Intensity, Spectrum and Size*, DOT HS 809 672. Washington, DC: National Highway Traffic Safety Administration.

[25] Flannagan MJ, Sivak M, Traube EC, Kojima S. 2000. Effects of overall low-beam intensity on seeing distance in the presence of glare. *Transportation Human Factors* 2(4): 313-330.

[26] Klauer SG, Dingus TA, Neale VL, Sudweeks, JD, Ramsey DJ. 2006. *The Impact of Driver Inattention on Near-Crash/Crash Risk: An Analysis Using the 100-Car Naturalistic Driving Study Data*, DOT HS 810 594. Washington, DC: National Highway Traffic Safety Administration.

scattered to some extent. This scattering becomes worse as we age. When a glare light is present, the scattered light in the eye acts like a "veil" and reduces the contrast of objects in the field of view (contrast here refers to the brightness of an object relative to the brightness of its background; as this difference increases, so does an object's contrast).[12] The contrast of an object determines, in part, how accurately and quickly it can be seen,[27] and even if it can be seen at all. The closer a glare light is to one's line of sight, the brighter the "veil" will be, and the greater the reduction in visibility will be.[28] This effect is known as *disability glare.*

The mechanisms behind disability glare have been understood since the 1920s,[29] and precise calculations of the reductions in contrast (and visibility) from any glare light for a given intensity and angle with respect to an onlooker are possible. The greater the intensity of the glare light, and the closer the glare light is to where one is looking (such as along a two-lane rather than along a four-lane highway), the greater the disability glare.[30] From a practical point of view, the scattered light that causes disability glare can have the following effects, which have been measured in several different laboratory and field studies:

- *Making difficult-to-see objects invisible.* All objects require a minimum amount of contrast against their backgrounds to be seen; otherwise they will be invisible. The amount of this *threshold contrast* differs for every object.[31] For example, a small object such as a white golf ball requires a higher contrast to be seen than a larger object at the same distance such as a

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[27] Rea MS, Ouellette MJ. 1991. Relative visual performance: A basis for application. *Lighting Research and Technology* 23(3): 135-144.

[28] Fry GA. 1954. Evaluating disability effects of approaching headlamps. *Highway Research Bulletin* (89): 38-42.

[29] Holladay L. 1926. The fundamentals of glare and visibility. *Journal of the Optical Society of America* 41: 235-244.

[30] Stiles WS, Crawford BH. 1937. The effect of a glaring light source on extrafoveal vision. *Proceedings of the Royal Society of London, Series B, Biological Sciences* 122(827): 255-280.

[31] Nadler MP, Miller D, Nadler DJ. 1990. *Glare and Contrast Sensitivity for Clinicians.* New York, NY: Springer-Verlag.

white soccer ball. If an object's contrast is close to the observed threshold contrast, the "veil" from scattered light inside the eye could be enough to reduce its contrast below a person's threshold, making the object invisible.

- *Decreasing visibility distance.* When driving, the ability to see objects when they are far enough away that the driver can take appropriate action in time is critical.[3] The distance at which an object can be seen is known as the *visibility distance*. This distance is reduced when disability glare is present; the greater the disability glare, the shorter the visibility distance.[32]
- *Increasing reaction times.* The speed with which someone can detect an object in the roadway is another way to measure visibility.[27] A recent field study of headlamp glare sponsored by NHTSA showed that as the intensity of oncoming headlamps increased, the reaction times by people became longer.[24]
- *Reducing detection probability.* In the same NHTSA-sponsored field study described immediately above, if targets were not seen within one second, it was unlikely that they would be seen at all.[33] Thus, another measure of the impact of disability glare is the likelihood that a given object in the field of view will be detected within one second. Just as increased glare intensity increases reaction times, more glare also increases the percentage of times that people cannot see objects.

The effects described above all are measured when the glare light is seen in the field of view, but as mentioned above, glare has a lasting effect after the glare light has gone away. Vision is, in part, a photochemical process in the eye, where light changes the chemistry of the eye's receptors. In turn, this reaction stimulates electrical signals that are carried by nerves to the brain

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[32] Mortimer RG. 1969. Requirements for automobile exterior lighting. In *Visual Factors in Transportation Systems*. Washington, DC: National Academy of Sciences.

[33] Bullough JD, Van Derlofske J, Dee P, Chen J, Akashi Y. 2003. Impact of headlamp glare on peripheral visibility. In *Progress in Automobile Lighting Symposium 2003* (pp. 166-180), Darmstadt University of Technology, Germany, September 23-24. München, Germany: Herbert Utz Verlag.

to be decoded into perceptions.[12] Following light exposure, the chemicals revert to their original state, but this process takes time, during which the eye's receptors are somewhat desensitized. For this reason, vision is initially difficult when just entering a dark area such as a dimly lighted tunnel from an open roadway on a sunny day, until a few seconds have passed. Light from oncoming headlamps can have the same effect, creating a *recovery time* after seeing the lights for the eyes to recover.[34] During this time, objects can be invisible or difficult to see.

The recovery time from glare depends upon the intensity of a glare light and the duration of exposure to the light. In a laboratory study sponsored by NHTSA, participants' recovery time depended on the *dosage* of light exposure, which is defined as the product of its intensity and the length of exposure (duration).[18] The higher the dosage, the longer the recovery time was.

What other effects does glare have besides reduced visibility?

> *Headlamp glare can cause discomfort even when it does not significantly affect visibility.*

The discussion above describes the ways in which glare can reduce visibility (disability glare) by making objects harder to see, either when a glare light is visible or shortly afterward. Glare has other effects on people as well. Perhaps the best known effect is discomfort. *Discomfort glare* is the sensation of annoyance, or even pain, that we experience when we see a bright light in our field of view.[35] While it would seem that using separate terms, *disability glare* and *discomfort glare*, to describe the effects of glare is like splitting hairs,[36] they really are different phenomena. Consider driving on a clear day. The light

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[34] Ottander C. 1963. Adaptation time after glare. In *Lighting Problems in Highway Traffic*. Inglestam E, ed. New York, NY: Macmillan.

[35] Boyce PR. 2003. *Human Factors in Lighting*, 2nd ed. New York, NY: Taylor and Francis.

[36] Sivak M, Flannagan MJ. 1993. Human factors considerations in the design of vehicle headlamps and signal lamps. In *Automotive Ergonomics.* Peacock B, Karwowski W, eds. London, UK: Taylor and Francis.

entering the eyes from outside the car can cause disability glare for seeing the dashboard instruments, even if it is not felt as uncomfortable. And, as will be discussed below, two glare lights that have the same negative impact on visibility can result in different amounts of discomfort.

Discomfort is most commonly studied in various experiments by asking subjects to provide a numerical rating using a subjective rating scale. The following is the most commonly used scale used in headlamp glare research (known as the De Boer scale):[37]

1. unbearable
2.
3. disturbing
4.
5. just permissible
6.
7. satisfactory
8.
9. just noticeable

Other types of measures of discomfort glare have been used in research studies. Responses like pupil size,[38] muscle tension around the eyes,[39] and even brain waves[40] have been measured in

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[37] De Boer JB. 1967. Visual perception in road traffic and the field of vision of the motorist. In *Public Lighting*. Eindhoven, Netherlands: Philips Technical Library.

[38] Hopkinson RG. 1956. Glare discomfort and pupil diameter. *Journal of the Optical Society of America* 46(8): 649-656.

[39] Berman SM, Bullimore MA, Jacobs RJ, Bailey IL, Gandhi N. 1994. An objective measure of discomfort glare. *Journal of the Illuminating Engineering Society* 23: 40–49.

attempts to replace subjective rating scales, but none have been satisfactory or consistent in the results yielded. Asking people to give numerical ratings can however produce very consistent and repeatable results if experiments are conducted properly.[41]

Drivers are much more aware of how a glare light makes them feel than of how much it might reduce their visibility. Some research has explored how important the sensation of discomfort is, even when not necessarily related to visibility while driving. Experiments that measured visibility showed that subjects' ratings of discomfort or of the quality of lighting (in terms of its ability to support visibility) rarely agreed with their actual visual performance.[42] In the NHTSA-supported study that showed that the dosage (the product of intensity and duration of light exposure) of glare exposure determined recovery times. Subjects' discomfort ratings were related to the peak intensity of the glare source rather than the duration or the dosage.[18] A glare light with a lower intensity for a longer time resulted in equal recovery times as a glare light with a higher intensity for a shorter time when the overall dosage was the same. However, subjects rated the higher intensity light as more problematic, even if the dosage was lower.

Perhaps a more important question about the potential importance of discomfort glare relates to whether discomfort glare causes people to change their behavior while driving. As discussed below, NHTSA-sponsored research[24] has confirmed other work[23] demonstrating that the bluer color of HID headlamps makes them more uncomfortable than conventional halogen headlamps.

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[40] Emdad R, Belkic K, Theorell T, Cizinsky S, Savic C, Olsson K. 1998. Psychophysiologic sensitization to headlamp glare among professional drivers with and without cardiovascular disease. *Journal of Occupational Health and Psychology* 3(2): 147-160.

[41] Schmidt-Clausen HJ, Bindels JTH. 1974. Assessment of discomfort glare in motor vehicle lighting. *Lighting Research and Technology* 6(2): 79-88.

[42] Rea MS, Bierman A, McGowan T, Dickey F, Havard J. 1997. A field study comparing the effectiveness of metal halide and high pressure sodium illuminants under mesopic conditions. *Proceedings of CIE Symposium on Visual Scales: Photometric and Colorimetric Aspects* (pp. 60-64), Teddington, UK. Vienna, Austria: Commission Internationale de l'Éclairage.

Other research supported by NHTSA indicates that drivers might look at oncoming HID headlamps for longer durations than conventional headlamps, resulting in a larger dosage, which reduces visibility.[43]

A NHTSA-sponsored naturalistic study showed that drivers tended to slow down following exposure to oncoming headlamps.[44] Evidence also exists that some drivers drift slightly in their lane when exposed to oncoming headlamps (with about as many drivers drifting toward the edge of the road as toward the center of the road).[45] One could argue that slowing down actually increases safety, because it is an appropriate response to reduced visibility of the roadway. However, glare that reduces visibility of the roadway can also make hard-to-see objects, perhaps including pedestrians along the edge of the road, invisible. If drivers were not aware that such objects are not visible, they might not adjust their driving behavior to reflect the inability to see these other objects. The safety implications of slight drifts in either direction are also unknown, but again may reflect a loss in visibility. Nevertheless, the evidence is beginning to show that glare from headlamps can affect driving behavior in reliable ways. Experiencing discomfort glare over longer periods of time (such as during a several-hour driving session) might affect driving behavior differently, but the evidence for this is contradictory.[46,47]

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[43] Aktan F, Schnell T. 2003. Glare induced by automobile headlamps: A statistical analysis of driver eye fixation behavior. *Spring Research Conference on Statistics in Industry and Technology* (p. 7), Dayton, OH, June 4-6. Dayton, OH: University of Dayton.

[44] Bullough JD, Van Derlofske J. 2005. Methods for assessing the impact of oncoming glare on driving behavior (SAE paper 2005-01-0442). In *Lighting Technology and Human Factors* (pp. 21-26), SP-1932. Warrendale, PA: Society of Automotive Engineers.

[45] Lighting Research Center, Rensselaer Polytechnic Institute. 2005. *An Exploratory Investigation of Illumination from Oncoming Headlamps in a Naturalistic Context* [report submitted to NHTSA]. Troy, NY: Rensselaer Polytechnic Institute.

[46] Ranney TA, Masalonis AJ, Simmons LA. 1996. Immediate and long-term effects of glare from following vehicles on target detection in driving simulator. *Transportation Research Record* (1550): 16-22.

[47] Schiflett SG, Cadena DG, Hemion RG. 1969. *Headlight Glare Effects on Driver Fatigue*, AR-699. San Antonio, TX: Southwest Research Institute.

Outside of the headlamp glare area, many studies of the effects of fatigue,[48] stress,[49,50,51,52] restricted visibility[53] and distraction[54] on driving behavior have been conducted. These studies have measured driving responses such as driving speed, following distance behind other vehicles, brake pedal pressure when stopping, lane position, eye blinking, and changes in steering wheel position. Again, some of these responses are easier to relate to potential driving safety, such as eye blinking, which presumably means a driver's eyes would be closed more often and that the driver would perhaps be less likely to see a sudden hazard.

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[48] Summala H, Hakkanen H, Mikkola T, Sinkkonen J. 1999. Task effects on fatigue symptoms in overnight driving. *Ergonomics* 42(6): 798-806.

[49] Chiang DP, Brooks AM, Weir DH. 2004. On the highway measures of driver glance behavior with an example automobile navigation system. *Applied Ergonomics* 35(3): 215-223.

[50] Daanen HA, Van de Vliert E, Huang X. 2003. Driving performance in cold, warm, and thermoneutral environments. *Applied Ergonomics* 34(6): 597-602.

[51] Steyvers FJ, De Waard D. 2000. Road-edge delineation in rural areas: Effects on driving behaviour. *Ergonomics* 43(2): 223-238.

[52] Godley ST, Triggs TJ, Fildes BN. 2004. Perceptual lane width, wide perceptual road centre markings and driving speeds. *Ergonomics* 47(3): 237-256.

[53] Ward NJ, Wilde GJ. 1995. Field observation of advance warning/advisory signage for passive railway crossings with restricted lateral sightline visibility: An experimental investigation. *Accident Analysis and Prevention* 27(2): 185-197.

[54] Lansdown TC, Brook-Carter N, Kersloot T. 2004. Distraction from multiple in-vehicle secondary tasks: Vehicle performance and mental workload implications. *Ergonomics* 47(1): 91-104.

4. WHY IS GLARE ESPECIALLY PROBLEMATIC ON TWO-LANE HIGHWAYS?

Two lane highways may present the "worst-case" scenario for headlamp glare.

As discussed previously, glare is an inherent aspect of driving at night because of the small size and high brightness of headlamps. For a number of reasons, two-lane highways, where one lane of traffic opposes another lane of traffic, present some of the worst conditions for nighttime glare. These reasons described subsequently include:

- Light levels can be lower than on other types of roadways
- Oncoming traffic is more likely to be closer to a driver's line of sight
- Roadway geometry can be more complex
- Access to the roadway can be less restricted
- Lane markings are less likely to be present
- Pedestrians can be closer to traveling vehicles

Lower Light Levels

The speed, accuracy, and distance from which a person can see and recognize an object are influenced by the overall light level.[27] Light from pole mounted roadway lighting fixtures (in addition to vehicle headlamps) often allows objects to be seen more reliably and more quickly than on unlighted roadways.[27] Another factor contributing to visibility is the contrast of an object against its background.[27] Glare reduces visibility by producing a brightness veil that reduces the contrast of objects. Contrast reduction can be mitigated by higher light levels on the road.[55] In other words, low contrast objects can be seen better if the overall light level is increased.

Darker roads can make glare more problematic.

As described in Section 2 of this report, much of the U.S. roadway network is unlighted or is lighted with luminaires on fixed poles.[7] Current guidelines for roadway lighting from the American Association of State and Highway Transportation and Highway Officials (AASHTO)[56] provide guidance as to when fixed roadway lighting should be considered. Traffic volume is a factor in making the decisions to install fixed lighting. Two-lane highways, especially rural two lane highways, are designed to carry less volume than expressways, so fixed lighting is often unwarranted for many two-lane highways except at complex intersections.[56,57]

The sensation of glare is much larger on unlighted roads because one of the factors contributing to discomfort is the ratio in brightness between a glare light and the surrounding area – the greater the difference the greater the glare.[41] Thus, seeing a pair of oncoming headlamps during the day or on a lighted two-lane road would likely be less disturbing than seeing the same oncoming headlamps on an unlighted two-lane road.

[55] IESNA. 2000. *Roadway Lighting: ANSI Approved*. New York, NY: Illuminating Engineering Society of North America.

[56] AASHTO. 2005. *Roadway Lighting Design Guide*. Washington, DC: American Association of State Highway and Transportation Officials.

[57] Green ER, Agent KR, Barrett ML, Pigman JG. 2003. *Roadway Lighting and Driving Safety*, KTC-03-12. Lexington, KY: University of Kentucky.

Oncoming Traffic Closer to Driver's Line of Sight

Many freeways and some undivided highways have more than two lanes of traffic traveling in each direction. Because the right-hand lane is usually used as the main driving lane, a significant proportion of traffic on these roads is separated from oncoming traffic by more than two lanes. This separation results in oncoming traffic being seen further *off-axis* than if it were on an undivided, two-lane highway; see Figure 2. This has two effects: the light at the driver's eyes from oncoming headlamps is lower in intensity because headlamps produce less light further from the forward direction,[58] and the oncoming headlamps are further from the driver's direction of view down the roadway. Both of these factors combine to lessen the negative impacts of the glare light on visibility and comfort. On undivided, two lane roadways, both of these factors reduce drivers' visibility and increase discomfort.[41] The visual angle (θ) toward oncoming traffic can be more than three times larger on a multiple lane roadway (lower panel) than on a two-lane roadway (upper panel).

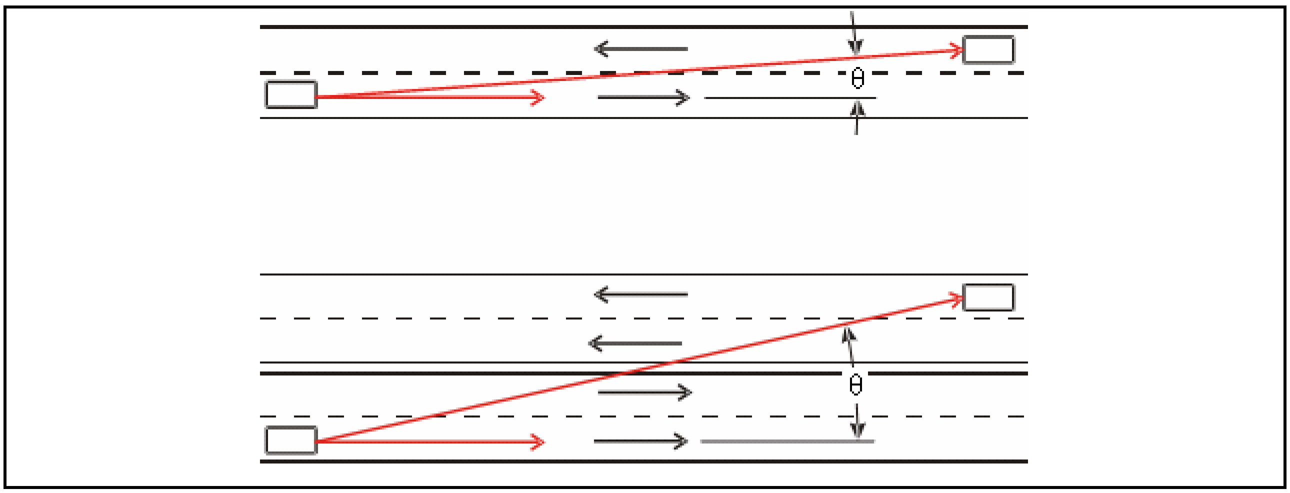

Figure 2. Effect of divided versus undivided highways on visual angle.

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[58] Van Derlofske J, Bullough JD, Hunter CM. 2002. *Visual benefits of high-intensity discharge automotive forward lighting*, SAE Technical Paper Series. No. 2002-01-0259. Warrendale, PA: Society of Automotive Engineers.

Glare screens, mechanical barriers in the center of the roadway, can block the view of oncoming traffic, thus reducing glare.[59] Although these screens could perhaps be used to advantage in multi-lane highways, they are not feasible for most two lane highways.

Complex Roadway Geometry

Freeways are designed to carry large amounts of traffic at very high speeds.[60] They therefore tend to be built without sharp curves or steep gradients that would make high-speed travel dangerous. Two-lane highways also carry traffic at moderately high driving speeds but can have sharper curves as well as hills and changes in elevation not found on freeways.[60] These more complicated roadway geometries expose drivers on two-lane roadways to a greater range of oncoming headlamp glare.

Consider a right-hand curve as illustrated in Figure 3. As the first driver begins to turn the vehicle into the curve, the headlamps on this vehicle must also begin to turn. Because headlamps produce higher light levels toward the passenger side of the vehicle,[58] traffic coming from the opposite direction will be exposed to higher light levels than would normally be experienced if the same vehicles approached one another on a straight road. The impact of higher light levels from oncoming traffic can be made even worse if the driver needs to look at the center line that is closer to the headlamps of the oncoming vehicle in order to safely navigate the curve.[61] Higher levels will increase *discomfort glare*[41] and result in increased *disability glare* because the contrast-reducing veil of brightness in the eyes will be even brighter.

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[59] Mace D, Garvey P, Porter RJ, Schwab R, Adrian W. 2001. *Countermeasures for Reducing the Effects of Headlamp Glare*. Washington, DC: AAA Foundation for Traffic Safety.

[60] AASHTO. 2004. *A Policy on Geometric Design of Highways and Streets*, 5th Edition. Washington, DC: American Association of State Highway and Transportation Officials.

[61] Bhise VD, Matle CC, Hoffmeister DH. 1984. *CHESS Model Applications in Headlamp Systems Evaluations*, SAE Paper No. 840046, Presented at 1984 SAE International Congress, Detroit, Michigan, February 1984.

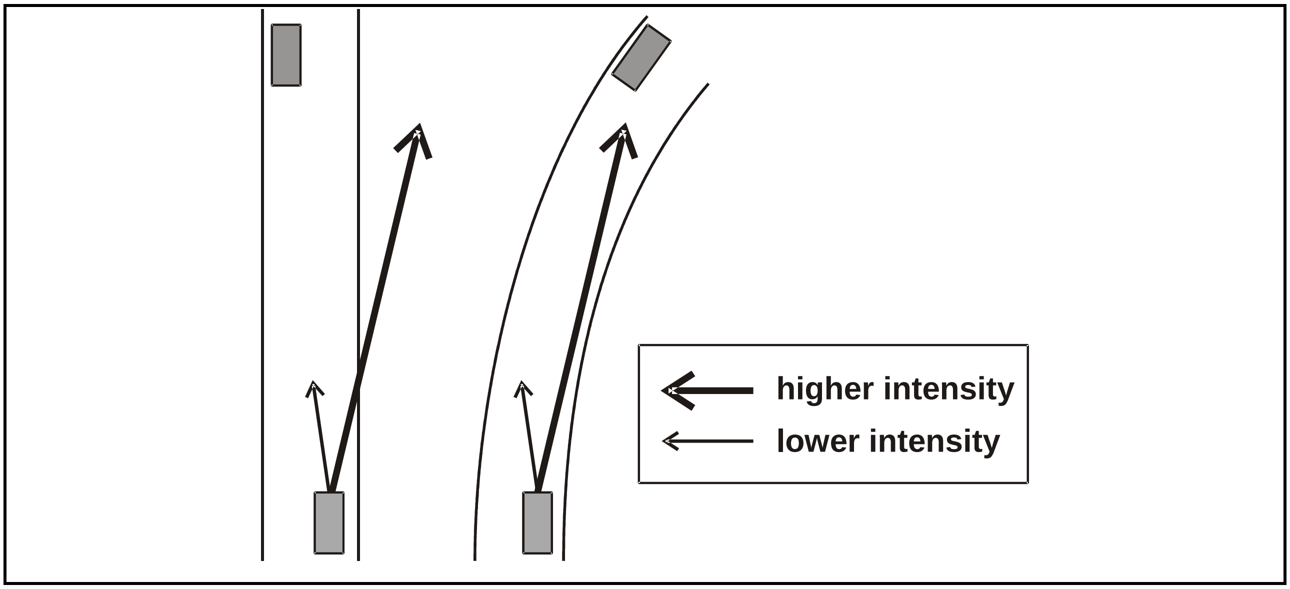

Figure 3. The effect of a curve on oncoming traffic glare exposure.

Less Restricted Roadway Access

Many two-lane highways can have abutting roadways or driveways that enter traffic directly, whereas freeways with multiple lanes are more likely to have exit and entrance ramps. Previous research,[62] including a study sponsored by NHTSA,[24] has demonstrated that discomfort from headlamp glare increases when the visual task is more difficult, such as on curvy roads. The potential for hazards along a two-lane highway is greater than along a divided, multiple-lane highway because vehicles can enter a two-lane highway from a variety of locations and directions. Two-lane highways are also usually not restricted in terms of bicycle travel or pedestrian use, unlike many divided multi-lane highways.[60] The greater hazard potential at any unknown location increases driving difficulty, making glare more uncomfortable and driving possibly less safe than on divided highways.[24,62]

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[62] Sivak, Flannagan, Ensing, Simmons. 1989. *Discomfort Glare is Task Dependent*, Report No. UMTRI-89-27, Ann Arbor, MI: University of Michigan, Transportation Research Institute.

Fewer Roadway Markings

Multi-lane highways tend to be well marked with indications for the traffic lanes on each side of the road as well as a clearly marked median.[63] Two lane highways, depending upon the amount of traffic they carry and their width, may not have median lines or edge lines to indicate the shoulder (if a shoulder is present); some very low volume roads and/or very narrow two lane highways have no markings at all.[64]

The purpose of roadway markings and delineation systems is to facilitate efficient and safe traffic movement along a roadway.[63] Perhaps no one would disagree with the observation that roadway markings make nighttime driving a much easier task. As with the roadway access issue, roadway markings in and of themselves have no direct impact on the amount of light that a driver is exposed to by oncoming headlamps. However, roadway markings can make the driving task easier by providing highly visible[65] guidance to a driver about the width of the road and the probable location(s) of oncoming vehicles, pedestrians or bicyclists. They can also alert drivers to the presence of curves or intersections before drivers might otherwise detect them on unmarked roadways.[66]

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[63] Federal Highway Administration. 2004. *Manual on Uniform Traffic Control Devices for Streets and Highways*, Revision 1. Washington, DC: U.S. Department of Transportation.

[64] Miller TR. 1993. *Benefit-cost analysis of lane marking*, Public Roads, 56:4. Washington, DC: Federal Highway Administration.

[65] Parker NA, Meja MSJ. 2003. *Evaluation of Performance of Permanent Pavement Markings*. Transportation Research Record 1824. Washington, DC: Transportation Research Board.

[66] Van Maren PA. 1980. *Correlation Of Design And Control Characteristics With Accidents At Rural Multi-Lane Highway Intersections In Indiana*. West Lafayette, IN: Purdue University and Indiana State Highway Commission.

Closer Proximity of Pedestrians

On two-lane highways, pedestrians can be closer to vehicle traffic than on other kinds of roads. In densely populated areas, sidewalks are common,[67] but they are less commonly found along two-lane highways in rural areas.[68] Although pedestrians might be less common, they are not restricted from using the roadway. If roadway lane markings are not present, as is the case on many two-lane highways,[64] there may be no clear boundary separating the area of the roadway used by drivers from that possibly used by pedestrians.

Pedestrians themselves are not always easily seen. Many types of clothing, such as dark coats and denim pants, have very low reflectance[68] and pedestrians wearing them do not provide much contrast against the roadway pavement or against the dark ground surfaces surrounding the road. Items such as reflectorized tags or clothing can dramatically increase a driver's ability to see a pedestrian,[69] but these items are not commonly used. Further, pedestrians themselves often overestimate how visible they are to oncoming traffic[70] and might engage in riskier behavior (such as remaining close to oncoming traffic for a longer period of time) than they otherwise would.

The greater proportion of pedestrians and the difficulty with which they are often seen at night[68,69,70] is another factor that can increase the difficulty of nighttime driving and, therefore, the impact of glare on both visibility and comfort.

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[67] AASHTO. 2004. *Guide for the Planning, Design, and Operation of Pedestrian Facilities*, 1st Edition. Washington, DC: American Association of State Highway and Transportation Officials.

[68] Dewar RE, Olson PL. 2002. *Human Factors in Traffic Safety*. AN: 00922829. Tucson, AZ: Lawyers & Judges Publishing Company, Inc.

[69] Sayer JR, Mefford ML. 2004. *The Roles of Retroreflective Arm Treatments and Arm Motion in Nighttime Pedestrian Conspicuity*. AN: 00985800. Ann Arbor, MI: University of Michigan, Transportation Research Institute.

[70] Tyrrell RA, Wood JM, Carberry TP. 2004. On-road measures of pedestrians' estimates of their own nighttime conspicuity. *Journal of Safety Research* 35(5):483-490.

Summary

The characteristics of two-lane roadways tend to result in lower overall light levels, smaller separation between oncoming vehicle and drivers' viewing locations, and an increased likelihood that light levels from oncoming headlamps will be increased. Moreover, the number of potential hazards is larger on two lane roadways, increasing the impact of glare for drivers. For these reasons, two-lane roadways present significant challenges in terms of reducing glare and its negative effects.

5. WHY IS GLARE MORE PROBLEMATIC FOR OLDER DRIVERS THAN FOR YOUNGER DRIVERS?

The visual system changes in several systematic ways as people age, resulting in differences that are important in the context of nighttime driving and headlamp glare. These differences can be categorized into two main groups:

- *Optical* factors
- *Neurological* factors

Both types of factors can make glare more of a problem for older drivers than for younger drivers.

What are the Optical Differences in the Eye Between Younger and Older Drivers?

> *The eyes of older drivers scatter light more than those of younger drivers.*

As described previously, the eye contains dead cells that scatter light and create a contrast-reducing veil of brightness. As people age, more of these materials accumulate in the eye. In addition, the cornea, the first refractive surface of the eye, and the crystalline lens, the variable focus mechanism in the eye, also begin to change with age. As the impact of ultraviolet radiation on these two refractive elements begins to accumulate, the collagen structures begin to change, increasing scatter light and reducing contrast sensitivity[71]. As more light is scattered, the brightness of the contrast-reducing

[71] Nadler MP, Miller D, Nadler DJ. 1990. *Glare and contrast sensitivity for clinicians*. New York, NY: Springer Verlag.

veil increases.[72] Thus, the contrast of a potential hazard against its background is typically lower for older drivers for the same headlamp intensity.[73]

With increasing age, the lens of the eye gradually yellows and increases in thickness and density.[74] Thicker and denser optical materials transmit less light, making already dark objects on or along the roadway harder to see. In addition, the eye's pupil is smaller for older adults than for younger adults;[75] the eye of an average 60-year-old allows less light – only about one third as much –into the eye as that of an average 20-year-old.[76] Therefore, older drivers can have a difficult time seeing at night due to the combination of less light reaching the retina and more of that light being scattered within the eye.

It should be noted, however, that individuals of the same age differ considerably in visual capabilities. Some older people have less scattered light and clearer optics than many younger people. On average however, the factors discussed here become more problematic with increasing age. Since visibility depends on light level and optical fidelity,[27] potential hazards for older drivers are generally less visible than for younger drivers.

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[72] Vos JJ. 1995. Age dependence of glare effects and their significance in terms of visual ergonomics. In: Adrian W (Ed). *Lighting for Aging Vision and Health*. Hendersonville, NC: Lighting Research Institute.

[73] Schieber F, Kline DW. 1994. *Age differences in the legibility of symbol highway signs as a function of luminance and glare level: a preliminary report.* Human Factors and Ergonomics Society, Incorporated.

[74] Weale RA. 1992. *The senescence of human vision*. Oxford, UK: Oxford University Press.

[75] Weale RA. 1982. *Contrast Sensitivity*. In: Woo, G. 1986. *Low Vision: Principles and Applications*. New York, NY: Springer-Verlag. 45-55.

[76] Wright GA, Rea MS. 1984. *Age a human factor in lighting*. Proceedings of the 1984 International Conference on Occupational Ergonomics, Vol. 1, Toronto, Ontario.

What are the Neurological Differences in the Eye between Younger and Older Drivers?

Neurological changes make driving more difficult and increase the effects of glare.

Once light passes into the eye and through the scattering materials inside, vision becomes a neurological process.[12] Light at the back of the eye reaches *photoreceptors*, which in turn create small electrical pulses that are carried by a network of nerves to the visual centers in the brain that are interpreted as visual information.[35] Degeneration of this network occurs naturally as we age,[77] and this degeneration is affected by one's lifelong light exposure history[78] and by genetic predispositions.[79] The three major retinal neurological problems associated with aging are macular degeneration (atrophy of the photoreceptors in the center of the eye's field of view), diabetic retinopathy (damage to the blood vessels nourishing the retina), and detached retina (separation of the layer of neurons and photoreceptors from the back of the eye).[80] Age-related macular degeneration is by far the most serious problem leading, in most cases, to termination of driving. Since these neural anomalies, even in early stages of disease development, make objects less visible, they tend to exacerbate the effects of glare.[24. 63]

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[77] Devaney KO, Johnson HA. 1980. Neuron Loss in the aging visual cortex of man., *Journal of Gerontology.* 35:836-841.

[78] Taylor HR, West S, Munoz B, Rosenthal FS, Bressler SB, Bressler NM. 1992. The long-term effects of visible light on the eye. *Arch Ophthalmology*. Jan. 110(1):99-104.

[79] Yang Z, Camp NJ, Sun H, Tong Z, Gibbs D, Cameron DJ, Chen H, Zhao Y, Pearson E, Li X, Chien J, Dewan A, Harmon J, Bernstein PS, Shridhar V, Zabriskie NA, Hoh J, Howes K, Zhang K. 2006. A variant of the HTRA1 gene increases susceptibility to age-related macular degeneration. *Science* Oct 19 [Epub ahead of print].

[80] Figueiro MG. 2001. *Lighting the Way: Key to independence*. Healthcare Professional edition. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute.

The amount of time that the visual system takes to recover visibility following exposure to a glare light is also greater for older than for younger people.[81,82] NHTSA-sponsored research is showing that the same light *dosage* (the product of intensity times the duration of light exposure) negatively affects older drivers for a longer time than younger drivers. The speed with which the eye can readapt to changes in light levels also tends to be longer in older people than in younger people.[83]

As we age, the likelihood of glaucoma also increases. Glaucoma results from increased pressure inside the eye that permanently damages the peripheral retina, therefore limiting one's visual field.[35] This is especially relevant to driving because reduced visual fields can make nighttime glare less noticeable but with no less effect at reducing the contrast of objects along the roadway from scattered light.

Summary

Relative to younger drivers, older drivers tend to be affected more by nighttime glare. The reasons for this increased susceptibility are increased light scatter in the eye, less light entering the eye, and neurological damage of the retina. Combined, these factors make nighttime driving more difficult for typical older drivers.

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[81] Schieber F. 1992. *Aging and the senses*, in Birren JE, Sloan RB, Cohen G. (Eds.) *Handbook of Mental Health and Aging*. New York, NY: Academic Press. pp. 251-306.

[82] Collins M. 1989. The onset of prolonged glare recovery with age. *Ophthalmic and Physiological Optics* 9(4): 368-371.

[83] Higgins, KE, White JM. 1998. *Transient adaptation at low light levels: Effects of age*. Palo Alto, CA: Electric Power Research Institute, Lighting Research Office.

6. WHAT ARE THE RISKS OF GLARE?

Why is it Difficult to Link Glare and Visibility to Crash Risk?

Unlike the rather clear links between factors such as drug or alcohol use and crash risk,[84] the effects of glare on crash risk cannot be easily quantified. Police reports do contain references of nighttime crashes caused by poor visibility or glare. However, because glare is dependent upon specific geometric factors, such as the location of a headlamp in one's field of view, determining whether or how headlamp glare might have contributed to a particular incident, especially after the incident has occurred, is very difficult. Thus, other surrogate measures of the effects of glare on driving safety are used.

What are Reasonable Surrogates for Crash Risk?

Visibility is an important surrogate measure for crash risks related to glare.

An important surrogate for crash risk with respect to glare is reduced visibility, which has been discussed in previous sections of this report (section 3 of this report identifies several ways in which visibility can be measured). An analysis of more than 2000 crashes in the United Kingdom[85] indicated that perception errors (as opposed to factors such as vehicle failure or alcohol impairment) contributed, at least in part, to more than 40% of the crashes. As described previously, nighttime glare can make drivers temporarily blind to hazards on the road at night,

[84] Cummings P, Rivara FP, Olson CM, Smith KM. 2006. Changes in traffic crash mortality rates attributed to the use of alcohol, or lack of a seat belt, air bag, motorcycle helmet, or bicycle helmet, United States, 1982-2001. *Injury Prevention*, June;12(3):148-154.

[85] Hills BL. 1980. Vision, visibility, and perception in driving. *Perception*, 9(2):183-216.

and these effects are compounded on two-lane roadways and for older drivers. Temporary blindness from glare will obviously increase the chances of hitting those hazards. Logically then, an increase in the amount or duration of glare further increases the chances of hitting those hazards.

Factors related to nighttime glare *other than* direct reductions in visibility may also affect crash risk indirectly, particularly with respect to discomfort experienced by drivers in the presence of oncoming headlamps. Discomfort could be important if, as evidence from NHTSA's public comment docket suggests, people change their direction of view in the presence of glare.[86] If drivers look away from the road while oncoming headlamp glare is present, they might not be looking in the right location to detect potential hazards. This effect might be even more important for glare from following vehicle headlamps that is seen in rear-view mirrors,[87] since mirrors can provide important information to the driver about the presence of other vehicles and hazards around and behind a vehicle. If a driver is not vigilantly scanning important locations, particularly in mirrors, then this behavior could constitute an increase in crash risk. It should be noted that while many interior rear-view mirrors can be dimmed to mitigate the impact of glare, exterior side mirrors cannot be adjusted as readily.

If discomfort prevents drivers from using their mirrors, safety could be reduced.

As discussed previously, increased discomfort could also speed up fatigue while driving or lead to riskier behaviors such as erratic roadway lane positioning. The relationship between increased discomfort and these types of behaviors, as well as the possible impact of those behaviors on crash risk, is not well

[86] NHTSA Docket No. 8885. *NHTSA Seeks Public Comment on Headlamp Glare Issues*. Washington, DC: National Highway Traffic Safety Administration.

[87] Sivak M, Ensing M. 1989. *Human Factors Considerations in the Design of Truck Lighting, Signaling, and Rearview Mirrors*. AN: 00608570. Ann Arbor, MI: University of Michigan, Transportation Research Institute.

established, but the objective of ongoing NHTSA-sponsored research is to provide more definitive answers to these questions.

Obviously, headlamps cannot be eliminated for nighttime driving and will always cause some level of glare for most drivers. The dramatic level of recent complaints about new headlamp technologies,[86] however, brings into question whether glare is unnecessarily becoming a larger issue than it has been previously. Although complaints are often focused on the color of the new headlamp technologies, this is not the only possible contributing factor to glare. As described earlier, new headlamp technologies and new vehicle designs may combine with headlamp color to increase the level of glare and thereby exacerbate driver complaints. HID headlamps generate more light[11] and they can be located higher with respect to the road on an ever-growing percentage of light trucks and sport utility vehicles on the road,[13] resulting in higher light levels for oncoming drivers. Even though the alignment of these headlamps must meet Society of Automotive Engineers standards[14] when manufactured, they may very well become improperly aimed[17] after the vehicle has been driven many miles, after damage to the vehicle, or simply with changes in vehicle loads. The combination of new headlamp color, higher light output, higher mounting heights, and improper aim may, in fact, increase the prevalence of glare on American roads, thereby reducing visibility and comfort, and increasing crash risks by making hazards less visible. These factors are discussed in greater detail in the subsequent section of this report.

7. WHAT FACTORS CONTRIBUTE TO GLARE AND ITS RISKS?

Preceding sections of this report discussed what glare is, how it affects vision and behavior, and why it is more problematic in certain locations (e.g., two-lane roadways) and for certain individuals (e.g., older drivers). This section discusses the potential impact of various factors related to vehicles and headlamps on glare and crash risk.

What Characteristics of the Vehicle and Its Lamps Affect Glare?

Headlamp Mounting Height

Headlamp beam distributions are defined without regard to headlamp mounting height.

Although the standards for required headlamp beam distributions[14] are consistent for passenger cars, light trucks and sport utility vehicles, these standards are defined with respect to the headlamp without regard for the eventual mounting height in these types of vehicles. (Note: Distributions for headlamps mounted on heavy trucks, for example, must adhere to different standards.[16]) In general, increasing headlamp mounting height results in improved visibility, as measured using visibility distance. This is because the region of maximum intensity tends to be increased in the vertical direction, resulting in potentially higher illuminances down the roadway (refer to Figure 1). NHTSA-sponsored research involving computer simulations of visibility distances for several different vehicles' headlamp systems mounted at different heights[88] demonstrated that headlamps with greater mounting heights tended to result in longer visibility distances down the roadway. However, there was large variability in this trend, so that some individual lamps with lower mounting heights can provide greater visibility distances than some others with higher mounting heights.

This potential visibility improvement with high-mounted headlamps must be balanced against the generally higher potential to produce glare to oncoming drivers. Research sponsored by NHTSA[88] has also shown that increasing headlamp height results in higher light levels at the eyes of oncoming drivers, both in meeting situations and when headlamps are seen in rearview mirrors.[89] Again, there is substantial variability among different headlamps so that this general trend may not be applicable to individual headlamps. In other words, it is not necessarily true that one headlamp set with a higher mounting height than another necessarily produces more glare. Higher light levels can increase disability glare, and increase the probability that a driver will not be able to see objects along the roadway. The higher levels can also increase the sensation of discomfort experienced by drivers exposed to those levels,[89] and if experienced in rearview mirrors, could make people avoid looking behind them while driving. Proposals to reduce headlamp mounting height have been made,[90] although none to date have been enacted.

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[88] Lighting Research Center. 2005. *Assessment of Headlamp Glare and Potential Countermeasures: The Effects of Headlamp Mounting Height* [report submitted to National Highway Traffic Safety Administration]. Troy, NY: Rensselaer Polytechnic Institute.

[89] Akashi Y, Van Derlofske J, Bullough JD. 2005. Recommendations for dimming headlamps through AFS. *Proceedings of the 6th International Symposium on Automotive Lighting*, Darmstadt, Germany. Munchen: Herbert Utz.

[90] Society of Automotive Engineers. 2001. *Headlamp Mounting Height for Passenger and Pickup Truck Vehicles*, SAE J2584. Warrendale, PA: Society of Automotive Engineers.

Lamp Aim

Fewer states have been requiring proper headlamp aim.

Most research into the effects of forward lighting on driver visibility and glare to oncoming drivers assumes that all headlamps are properly aimed, according to the standards set forth by the Society of Automotive Engineers (SAE) for the aiming of headlamps.[14] These standards require headlamps to be aimed within 0.76 degrees (up or down) of proper aim. In the U.S., headlamp aim is not a Federal requirement, but some states have implemented the same industry standards mentioned earlier in this report. In recent years, fewer states have required regular checking of headlamp aim as part of the vehicle inspection process.[91] Research commissioned by NHTSA in the early 1990s showed that improper aiming of headlamps was nearly as common in a state that addressed headlamp aim in vehicle inspection (Virginia) as in a neighboring state that did not have such requirements (Maryland).[92] As described earlier, in a more recent NHTSA-sponsored study conducted in New York State, the majority of vehicles had at least one headlamp that was improperly aimed either upward or downward.[17] Further, while not related to improperly aimed headlamps, changes in roadway grade and elevation along hills and slopes can result in very different light levels ahead of the vehicle and toward oncoming drivers because in these situations the entire vehicle pitch changes relative to the ground.

Headlamps aimed downward result in lower light levels ahead of a vehicle, effectively moving the location of the headlamp beam distribution with the highest intensity closer to the vehicle.[15]

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[91] Texas Department of Public Safety. 2000. *Why Don't We Aim Headlamps Anymore?* Austin, TX: Texas Department of Public Safety. Accessed on 5 October 2006 at http://www.txdps.state.tx.us/vi/misc/faq/faq_item.htm.

[92] Copenhaver MM, Jones RE. 1992. *Measurement of Headlamp Aim and the Electrical and Photometric Performance Characteristics of Rear Lighting Systems*, DOT HS 807 930. Washington, DC: National Highway Traffic Safety Administration.

When headlamps are aimed upward, glare increases for oncoming drivers, as well as for drivers ahead of the vehicle looking in their rear view mirrors. NHTSA-sponsored research shows that headlamps aimed upward by even one degree will create enough glare for oncoming drivers to reduce the distances at which objects along the roadway can be seen.[93]

Headlamps aimed upward will also result in increased dosages of light exposure (intensity × duration) when two vehicles meet while driving in opposite directions. These increases can be large for new headlamp types. For example, in a study sponsored by NHTSA,[15] the distributions of several halogen and HID headlamps were compared using simulation software. When both types of headlamps were aimed properly, the halogen headlamps studied tended, on average, to produce similar glare dosages as the HID headlamps studied. When the headlamps were improperly aimed upward by 1.5 degrees, the halogen headlamps could produce a dosage more than ten times that from properly aimed halogen and HID headlamps, and when aimed similarly upward, HID headlamps could result in even higher dosages than halogen headlamps. Since the time to recover visibility of objects is related to the glare dosage,[18] improperly (and upwardly) aimed headlamps can cause objects to remain invisible to oncoming drivers for longer durations than properly aimed headlamps.

In addition to headlamps, there is some concern with glare associated with the aim of auxiliary lamps. These lamps are not regulated, and only some have the ability to be aimed accurately.

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[93] Lighting Research Center. 2006. Sensitivity Analysis of Headlamp Parameters Affecting Visibility and Glare [progress update to National Highway Traffic Safety Administration]. Troy, NY: Rensselaer Polytechnic Institute.

Headlamp Beam Distribution

Halogen and HID headlamps must conform to the same standards.

As noted in preceding sections of this report, vehicle headlamps must conform to specific requirements for minimum light levels in regions of the beam that are most likely to contribute to forward visibility, and maximum light levels in regions that could result in glare to oncoming drivers, or glare in rear view mirrors.[14] The requirements are the same regardless of the light source used in the headlamps; halogen headlamps and HID headlamps, for example, must conform to the same set of minimum and maximum light levels at the same locations within the beam distribution. Some locations within the required beam distribution are not restricted, either by minimum or maximum light levels, such as the area that contains light directed downward and toward the left (from the driver's perspective).[14] In other words, current headlamp standards allow a very wide range of luminous intensities within certain locations in the headlamp beam. Clearly, if headlamps are improperly aimed or when variations in roadway geometries and in locations of potential hazards and oncoming vehicles are present, the fixed beam distribution from headlamps may not always provide adequate visibility, or prevent glare.

HID headlamps typically produce twice as much light as halogen headlamps.[11] Directing the light from a halogen headlamp into the regions with minimum requirements for light, while keeping below the maximum allowable light levels, tend to result in a smaller amount of "leftover" illumination that could be directed into less restricted regions. For many HID headlamps, there is a higher amount of "leftover" illumination, with this illumination often being directed to peripheral locations within the beam[58] and to other locations without restrictions on maximum light levels. Thus, many HID headlamps are more likely to produce high light levels to oncoming drivers when they are aimed upward than halogen headlamps aimed upward by the same amount.[15]

Presently, all standards for lighting on vehicles assume headlamps that are permanently fixed in terms of their distributions. Proposals for lighting on vehicles in the near future will likely include “adaptive lighting” that changes light levels and beam distributions in “real time” to respond to oncoming drivers, roadway geometries, and weather.

Headlamp Color

A frequently mentioned characteristic of headlamps by members of the driving public responding to NHTSA's request for public comments related to headlamp glare[19] is the "blue" color of HID headlamps compared to halogen headlamps. Indeed, NHTSA-sponsored research [24] and other studies[23,92] have confirmed that people experience more discomfort when exposed to the bluer HID headlamps than when they are exposed to the yellower halogen headlamps for the same measured light level at the eye. However, this increased discomfort from the bluer lights has not been demonstrated to translate into greater reductions in visibility for objects viewed on-axis[25.,96] nor off-axis,[24] reinforcing the theory that discomfort and disability are separate phenomena.

Headlamp Optical System

Prior to the 1980s, vehicle headlamps consisted only of sealed beam filament lamps. For these lamps, the entire headlamp included the light source with a reflector and lenses to produce the required beam distribution.[12] Since that time, headlamps with dedicated reflectors and lenses have become available, so that only a capsule-like bulb is replaced when a headlamp fails.

Projector style headlamps have become more common.

More recently, projector style headlamps have become more common. In these units, an optical mechanism not unlike a slide projector produces the required headlamp beam distribution. The lighted area of projector headlamps can be quite small, in comparison with reflector headlamps. Some evidence exists that this smaller size can result in greater discomfort when headlamps are viewed from relatively close distances.[94] However, when viewed from more than approximately 100 feet, the size of a headlamp has little impact on discomfort, according to NHTSA-commissioned research.[24] No research has identified any impact of oncoming headlamp size on visibility; the same NHTSA study[24] showed that headlamps of different sizes, even differing in area by a factor of nearly ten, but producing the same light level at oncoming drivers' eye, resulted in equal visual performance for individuals exposed to those headlamps.

Headlamp and Windshield Cleanliness and Condition

Particularly during and following conditions of poor weather, headlamps and vehicle windshields and mirrors can become soiled and even damaged by dirt, salt or sand. Just as material inside the eye scatters light, dirt or spray build-up on windshields, mirrors or the outer surfaces of headlamps will also scatter light. In the case of dirty or scratched windshields or mirrors, the contrast of objects along the roadway will be reduced by scattered light[12] potentially making some objects invisible that otherwise would have been visible. When the outer surfaces of headlamps are dirty or damaged, the light distribution can be altered, possibly enough so that the resulting visibility for the driver using those headlamps is reduced or so that the light levels produced in the direction of oncoming drivers is increased.[95] However, the size of the reductions in light level for forward visibility and of the increases in light levels for oncoming drivers were much smaller than those found to be caused by improper headlamp aim.[95]

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[94] Rosenhahn EO, Lampen M. 2004. New investigation of the subjective glare effect or projection type headlamps. In *Lighting*, SP-1875 (p. 205). Warrendale, PA: Society of Automotive Engineers.

[95] Alferdinck JWAM, Padmos P. 1998. Car headlamps: Influence of dirt, age and poor aim on glare and illumination intensities. *Lighting Research and Technology* 10: 195-198.

Conclusions

Table 1 summarizes the factors described above, with a set of potential proposals that can be envisioned to reduce headlamp glare and its effects on driving performance. This summary does not consider potential measures to reduce glare that involve changes in roadway design, such as wider medians or glare screens, which are summarized elsewhere.[59]

A review of the characteristics of headlamps and vehicles that contribute to headlamp glare shows that beam patterns, aim, and mounting height, and the interaction between these characteristics, can play a large role in the light levels reaching the eyes of oncoming drivers (especially on unlighted, two lane highways). This in turn makes some objects invisible to drivers, particularly older drivers. Importantly, these characteristics have changed in parallel during recent years,[13,91] potentially compounding the negative effects of glare more so than any factor alone. Results from a recently completed series of experiments sponsored by the Federal Highway Administration largely confirm these findings.[96]

European standards for vehicle headlamps[97] have different aiming requirements for headlamps with different mounting heights, but it should be noted that European headlamps adhere to different requirements for light distribution than those in the U.S. Factors such as headlamp color, particularly the bluish appearance of HID headlamps, and the increasing prevalence of projector headlamps, can further compound the sensation of annoyance and discomfort experienced by many American drivers.[19] Added to these factors is the fact that the American driving public is aging[98] and is more sensitive to the deleterious and discomforting effects of

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[96] Federal Highway Administration, December 2005. *Enhanced Night Visibility Series (Volumes I through XVIII),* Washington, D.C.; U.S. Department of Transportation

[97] ECE No. 48

[98] American Public Transportation Association. 2003. *Mobility for the Aging Population.* Washington, DC: American Public Transportation Association.

headlamp glare than the younger driving public of earlier decades. These factors in combination appear to explain much of the passion of the American driving public regarding headlamp glare.

To some extent, headlamp glare is unavoidable. Headlamps must facilitate visibility at great distances, something that can only be accomplished by bright lights having the potential to produce high light levels in the forward scene. Present standards for headlamps,[14] in principle, work to strike the proper balance between visibility and glare, but these standards are silent with respect to headlamp aim, and do not differentiate among a wide range of headlamp mounting heights.

New headlamp technologies (e.g., light emitting diodes), even newer than HID and projector headlamps, are beginning to be introduced on vehicles in the United States. Headlamps with distributions that change in response to driving conditions (e.g., poor weather, curves in roadways, the presence of pedestrians, or the presence of oncoming vehicles) are likely to be included on vehicles of the future.[99,100] Already, "steerable" headlamps that turn with the steering wheel into curves are standard equipment on some vehicles sold in this country. Headlamp functions presently classified under the term "advanced forward-lighting systems (AFS)" are not addressed by current headlamp requirements.

Indeed, new headlamp systems may aid in reducing the tradeoff between visibility and glare by allowing systems to respond dynamically to the driving situation. At the same time, these dynamic headlamp systems will present new challenges for regulation of vehicle lighting. By conducting research into driver needs, NHTSA is working to gain the knowledge necessary to

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[99] Kobayashi S, Hayakawa M. 2003. Beam controllable headlamping system (SAE paper 910829). In *Advances in Lighting Technology*, PT-98 (p. 3). Warrendale, PA: Society of Automotive Engineers.

[100] Sivak M, Flannagan MJ, Schoette B, Nakata Y. 2003. Benefits of applying adaptive headlamping to the current U.S. and European low-beam patterns (SAE paper 2002-01-0524). In *Advances in Lighting Technology*, PT-98 (p. 73). Warrendale, PA: Society of Automotive Engineers.

develop reasonable requirements for vehicle headlamps that will be flexible, and ultimately beneficial for the American driving public.

Among the research activities underway are:

- Analyses to compare the relative effects of headlamp mounting height, headlamp light source, headlamp aim and headlamp beam characteristics on forward visibility and on glare to oncoming drivers along two-lane roadways. These will help identify priorities for effective glare countermeasures.
- Assessment of headlamp aim on a representative sample of vehicles. This activity will help identify the extent and causes of improper headlamp aim.
- A field experiment to study visual performance of older drivers following exposure to light creating glare. This activity will help clarify the impact of age and light level on recovery from glare under realistic conditions.
- An on-road study of the effects of different levels of glare on driving behaviors (such as visual distraction). This activity will identify light levels that start to affect driving performance."
- Development of a prototype safety-based adaptive headlamp system based on driver's needs regarding visibility and glare reduction. The prototype will be used to develop an evaluation protocol to define performance requirements for adaptive lighting. Adaptive headlamps may afford new options for resolving the tradeoff between glare and visibility by automatically reducing glare when other drivers are nearby and increasing intensity under other conditions.

All of these activities are presently underway and will be documented in a subsequent report to Congress containing the findings and recommendations for NHTSA regarding priorities for mitigating the impacts of headlamp glare on U.S. highways while maintaining or increasing seeing distances.

Table 1. Summary of potential options for reducing nighttime glare and its effects on driving performance.

Headlamp/vehicle characteristic	Potential proposal	Possible effects on glare and driving performance
Mounting height	Reduce maximum headlamp mounting height	Reduced light levels to oncoming drivers; reduced forward visibility of drivers with lower-mounted headlamps
Aim	Require headlamp aim at the time of sale	More consistent light levels to oncoming drivers, visibility for driver; provide a consistent starting point from which to build other aiming requirements
	Conduct regular periodic headlamp aim adjustment	More consistent light levels to oncoming drivers, visibility for driver
	Use different aiming for headlamps with different mounting heights	More consistent light output in the forward scene and toward oncoming drivers
Beam distribution	Use different beam distributions for different mounting heights within allowable limits	More consistent light levels to oncoming drivers
	Reduce light levels in areas of beam distribution not presently restricted (e.g., foreground light that can create glare along hills or when headlamps are improperly aimed)	Reduced light levels to oncoming drivers
	Develop test protocols to evaluate the glare reducing potential of advanced/adaptive forward lighting system	Reduced light levels to oncoming drivers when they are present; increase forward visibility when oncoming drivers are not present; distributions that are more responsive to weather conditions
Color	Limit "blue" content of headlamps	Slightly reduced discomfort to oncoming drivers; slightly reduced off-axis visual performance for drivers using them
Optical design	Use a minimum lamp size/area	Slightly reduced discomfort to nearby oncoming drivers
Cleaning and maintenance	Use headlamp washing systems	Slightly reduced light levels toward oncoming drivers; slightly increased forward visibility for drivers using systems
	Conduct regular periodic check of windshields and headlamp lenses	Slightly reduced light levels toward oncoming drivers; slightly increased forward visibility for drivers using systems; slightly lower light levels at eyes of drivers with better-maintained windshields