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Improved Roadway Illumination: Information Resource

RATIONALE

SAE J2738 has been reaffirmed to comply with the SAE 5-Year Review policy.

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1. Scope

Headlamps should illuminate the traffic scene ahead of the vehicle in such a way that the driver can operate the vehicle safely and in a relaxed manner. At the same time, negative effects on drivers of other vehicles, pedestrians and other people should be minimized. Various technical parameters such as beam pattern, mounting height, headlamp aiming, and source spectrum can be tuned to find the necessary compromise. The physiology of the vision system under specific night time conditions strongly influences these factors and how headlamps can be best optimized for visibility and comfort. The SAE Improved Roadway Illumination task force collected and reviewed relevant research on these topics. This document is a comprehensive summary of this information. The goal is to enable lighting experts, advocacy groups, and non-experts (journalists, consumer organizations, car drivers) to better understand the benefits and tradeoffs of improved roadway lighting with modern headlamp technology. It should be noted that all studies can not be included in this report, but the intent of this document is to provide the reader with a representative sample of the existing research as a starting point. Further, this document can be updated in the future to reflect new research findings.

2. References

See Section 11 for references.

3. Introduction

This report outlines a literature review to further our understanding of vehicle forward lighting and how it can be best optimized for visibility and comfort.

3.1 Responses to Lighting

Forward lighting on vehicles serves a number of objectives that are to be met simultaneously for the vehicle driver and other roadway users. These include:

- providing adequate forward visibility on and along the roadway
- providing peripheral visibility so that potential hazards not yet along the roadway can be detected
- maximizing driver comfort while minimizing discomfort to other drivers
- providing attractive appearance

These responses serve as the end objectives of lighting from the user's point of view. In order to meet these objectives, lighting systems must be developed with the appropriate characteristics.

3.2 Characteristics of Lighting

It is not enough to say simply that a forward lighting system should "provide adequate forward visibility" or "maximize comfort." In order to meet these objectives, specific aspects of lighting can be manipulated. These aspects form the palette of the lighting system designer, and include:

- intensity or illuminance
- aim, shape, uniformity of the beam pattern
- change of beam pattern (intelligence)
- location and mounting height of the light sources
- effects of dirt and water
- spectral power distribution
- color
- system life and reliability

One of the objectives of the present report is to summarize existing information about these characteristics of lighting.

3.3 Research Methods

The information summarized in this report is based on a combination of techniques and methods, including:

- analytical methods based on calculation using existing models of expected performance
- short-term laboratory and field study methods, directly measuring lighting or testing human responses to lighting
- long-term laboratory and field study methods, using simulation or observational techniques to understand how responses might change under long-term exposure to different lighting conditions

In the present report, each of the characteristics or aspects of forward lighting are discussed with respect to the different methods of understanding them. Brief summaries of important investigations of these aspects of lighting are also provided.

4. Intensity and Illuminance

4.1 Analytical Methods

One of the most important factors related to the success of forward lighting systems is the intensity (or illuminance) the system provides. A number of quantitative models for predicting visual performance as a function of light level exist. One of the most important is the relative visual performance (RVP) model (Rea and Ouellette, 1991), which provides a prediction for the speed and accuracy of visual processing as a function of adaptation level, target size and contrast, and observer age. Another model used widely in the specification of roadway lighting in North America is the small target visibility (STV) model. Interestingly, this model does not incorporate the effects of headlamps, but it was found recently (Keck, 2001) that while the prediction for visibility provided by STV is not correlated with vehicle crashes, a modification of the model to incorporate headlamp illumination did result in a small but significant correlation with vehicle crashes, underscoring the importance of considering all roadway visibility elements.

In terms of peripheral visibility, few data are available upon which to make predictions. One recently developed model, still in preliminary form, uses the results of a series of similar investigations of forward visibility under headlamps and data on the detection of small targets located throughout the peripheral field of view. Combining results in this way provided a robust data set that provided a predictive model for peripheral visibility under different types of headlamp beams (Bullough, 2002).

Of course, not only forward visibility, but the potential for disability and discomfort glare are impacted by the intensity of a forward lighting system. Formulae for the prediction of disability glare (Fry, 1954) have been found to quite accurately predict the reduction in visibility that is caused by oncoming headlamps in the field of view. Similar formulae exist to predict the extent of discomfort felt under oncoming headlamp illumination (Schmidt-Clausen and Bindels, 1974), since discomfort and reduced visibility do not necessarily go hand in hand.

4.2 Laboratory and Field Methods

The study of forward visibility using field methods is common and generally has used techniques like the measurement of reaction times and missed targets (Van Derlofske et al., 2001, 2002) and target visibility distance in the field of view (Hamm and Steinhard, 1999). These results generally are in agreement with model predictions.

One technique for assessing long-term performance and impacts of forward lighting involves the use of surveys and questionnaires to gauge drivers' acceptance and opinions about forward lighting. A recent survey of snowplow operators to ask what types of forward lighting were most suitable when driving in snow were fond to exhibit excellent agreement with field studies comparing different forward lighting configurations (Eklund et al., 1997).

5. Aim and Shape of the Beam Pattern

5.1 Analytical Methods

One approach to understanding the impact of forward lighting beam patterns and aim is to quantify the types of forward lighting beam patterns used in a given jurisdiction. Market-weighted beam patterns providing average intensity values for a range of angles (i.e. Schoettle et al., 2001) provide useful analytical tools for estimating typical forward lighting configurations on the road. These data could be used in turn with models providing predictions of visibility and other responses. For example, Bullough and Rea (1997) developed a model to predict the impact of beam shape and aiming on subjective impressions of visibility and comfort while driving in poor weather. Such models and tools will be useful in the study of adaptive beam patterns that can adjust in responses to changes in the ambient environment.

5.2 Laboratory and Field Methods

The basis for many models to assess aim and beam pattern effectiveness will often need to be field studies where these patterns can be replicated most accurately. Comparisons of different beam pattern types for the distance at which targets can be detected is one such approach (Flannagan et al., 1995). Other responses to beam patterns might also be important, such as comfort while driving or even aesthetic appearance while performing a test drive. Studies of subjective impressions of headlamp beam uniformity have shown that this characteristic of lighting is often seen as important in providing visibility and maintaining visual comfort while driving (Schumann et al., 1997).

6. Location and Mounting Height

6.1 Analytical Methods

The mounting location and height of forward lighting sources can have a significant impact on driver visibility and comfort. Analytical tools for the assessment of the effects of these parameters include the model, described above, by Bullough and Rea (1997) to predict preferences of forward lighting as a function of mounting location, which in turn impacts the distance of the source from the line of sight. This factor is found to determine the intensity of back-reflected light in snow and fog conditions.

A simulation-based approach to predicting the effectiveness of forward lighting configurations was developed and refined by Mortimer (1974). Based on actual photometric measurements and responses to targets in field studies, a scenario-based simulation tool was developed that could then be used to compare various lighting configurations without conducting additional field studies.

6.2 Laboratory and Field Methods

Measurements of the range of conditions that can be experienced in the field is a useful approach to characterizing lighting. Field measurements of headlamp height and separation (Sivak et al., 2001) can provide data that will in turn support more refined laboratory and analytical approaches to studying lighting.

7. Dirt and Water

7.1 Analytical Methods

Few studies, if any, have provided tools for calculating or predicting the impact of dirt and water on forward lighting system performance.

7.2 Laboratory and Field Study Methods

All lighting and visibility systems along the roadway will undergo inevitable reductions in visibility caused by dirt or by water introduced by rain. These phenomena simultaneously reduce the illuminances produced by lighting systems in the points of their maximum intensity, reducing forward visibility, and increase illuminances along the points of their minimum intensity, potentially increasing glare. Studies of other visibility elements (e.g., signs, see Colomb and Michaut, 1986) can perhaps be useful in better understanding the effects of dirt and water on headlamps.

Of interest, a number of jurisdictions already require the use of headlamp cleaning devices in conjunction with certain headlamp technologies such as high intensity discharge headlamps. Thus the problem might be one of implementation countermeasures rather than changing lighting to adapt to conditions of dirt or water.

8. Spectral Power Distribution

8.1 Analytical Methods

For forward visibility in terms of color rendering, the commonly accepted industry metric for predicting the ability of a light source to render colors well is the color rendering index (CRI) (Rea, 2000). In effect, this metric compares a light source's ability to render colors similarly to a reference source, either an incandescent lamp (for a yellowish-white source) or daylight (for a bluish-white source), not necessarily one's ability to accurately identify colors under that source. The gamut area metric (Boyce, 2003) appears to better predict the ability of a light source to result in accurate color identification.

In terms of forward visibility, spectrum can play a role at mesopic light levels, where both cones and rods provide visual input, for peripheral vision (He et al., 1997). In fact, a model of photometry for mesopic light levels typically experienced while driving at night has been developed that quantitatively takes into account the impact of spectral power distribution on peripheral vision. Of interest, since only cones and no rods are found in the central part of the human retina, mesopic vision does not apply for on-axis visual tasks such as reading or detecting objects in the center of the roadway.

8.2 Laboratory and Field Methods

Color naming accuracy is a useful technique for assessing the impact of a light source to assist in proper identification of colors. A study using this technique (McColgan et al., 2002) demonstrated that there were no differences among halogen, high intensity discharge and coated halogen lamps in color naming accuracy despite their large differences in color rendering index.

As with the study of illuminance and intensity, experimental methods such as the measurement of reaction times and target detection have been used to successfully tease out the impact of spectral power distribution on peripheral visibility (He et al., 1997; Van Derlofske and Bullough, 2003).

In terms of glare, spectral power distribution has been demonstrated in several field and laboratory studies using these methods to have no significant impact on either on-axis or peripheral visibility. The same is not true for discomfort glare using subjective ratings of discomfort on scales such as the De Boer scale. Various studies in the laboratory and the field have shown that high intensity discharge headlamps resulted in somewhat greater discomfort even at the same illuminance (Bullough et al., 2002; Flannagan, 1999).

9. System Life and Reliability

9.1 Analytical Methods

Different forward lighting technologies have widely differing life and reliability characteristics. Filament-based halogen lamps have been the basis for headlamps for several decades, but increasing use HID headlamps (Jost, 1995) and the potential future use of light emitting diodes (Van Derlofske and McColgan, 2003) will result in very different assumptions for lamp and system life than are presently common. Rated life of these technologies is a thorny question given the very different operating conditions these systems undergo, in comparison to the relatively benign conditions they are often tested under.

9.2 Laboratory and Field Methods

It is important, in understanding life and reliability issues, to be able to quantify the actual hours of operation for which forward lighting is used. Observations of headlamp usage as a function of daylight availability (Boyce and Fan, 1994) can provide useful data in making accurate predictions.

Understanding life and reliability issues is also important because failure of a headlamp, for example, can be unnoticed for quite some time by a vehicle user, but will often result in significant reductions in visibility of objects along the roadway, such as traffic signs (Zwahlen et al., 1990).

10. Discussion

The previous discussion of the various aspects of lighting, in the context of the types of responses that are important and the types of methods that can be used to assess their optimal characteristics, can be used to provide a preliminary assessment of the relative importance of each aspect at affecting visibility, comfort and appearance. Of course while some of these aspects will be more important than others, it is equally important to understand the methods that are available to investigate and address these aspects.

11. References

11.1 Importance of Lighting

Driving at night is a challenging task that is growing in occurrence and importance in our society. People and goods must move regardless of the time of day. Lighting and visibility elements enable safe, comfortable roadway travel at night. It is readily apparent that lighting of roadways, both from vehicle forward lighting and from fixed pole lighting, can increase visibility. Research has also demonstrated that lighting can have a beneficial impact on safety by reducing crashes.

11.1.1 Lighting, Visibility and Crashes

Gimbel, H. V., Van Westenbrugge J. A., Johnson W. H., Willerscheidt A. B., Sun R., Ferensowicz M. 1993. Visual, refractive, and patient satisfaction results following bilateral photorefractive keratectomy for myopia. Refractive and Corneal Surgery 9; S5-S10.

- most patients having refractive surgery reported little or no problems with nighttime driving

Green, E., et al. 2003. Roadway Lighting and Driver Safety. Kentucky Transportation Center, KTC-03-12/SPR247-02-1F

- nighttime crashes were reduced by 45% after the addition of roadway lighting to some intersections

Hemion, R. H. 1969. A Preliminary Cost-Benefit Study of Headlight Glare Reduction, Report AR-683. San Antonio, TX: Southwest Research Institute.

- accidents in which headlight glare (or "blinding by headlights") could be stated as a cause numbered around 1% (or slightly less), based on results from several U.S. states

Olson, P. L., Aoki T., Battle D. S., Flannagan M. J. 1990. Development of a Headlight System Performance Evaluation Tool, Report UMTRI-90-41. Ann Arbor, MI: University of Michigan.

- an average adaptation luminance of 1 cd/m^2 while driving at night is derived

Wilken, D., et al. 2001. *European Road Lighting Technologies*. US DOT, Report Number FHWA-PL-01-034.

- after roadway lighting was installed, the following reductions in accidents, injuries and fatalities were reported: Finland: 20% to 30%; Norway: 65% (nighttime fatalities), 30% (injuries); Netherlands: 18% to 23%

11.1.2 CRASH STATISTICS

Hakamies-Blomqvist, L. 1994. Compensation in older drivers as reflected in their fatal accidents. Accident Analysis and Prevention 26(1): 107-112.
- relatively fewer accidents of older drivers occurred under difficult conditions than of younger drivers
- older drivers were less often in a hurry, intoxicated, or distracted by nondriving activities than others

National Safety Council. 2002. Driving at Night.
- traffic death rates are three times greater at night than during the day; 90% of a driver's reaction depends on vision, and vision is severely limited at night; depth perception, color recognition, and peripheral vision are compromised after sundown

Opiela, K., Andersen, C. K., Schertz, G. 2003. Driving after dark. Public Roads 66(4).
- the fatal crash rate for nighttime driving is three to four times that for daytime driving according to data in Traffic Safety Facts 2000
- an analysis of the Fatality Analysis Reporting System (FARS) data for 2000 reveals that: (1) 49% of all fatal crashes occur at night; (2) 81% of fatal crashes occur on dry pavement, both day and night; (3) 40% of all fatal crashes involve alcohol as a factor, with more than 60% of those occurring at night; and (4) problems with driver vision, vehicle hardware, or environmental conditions are cited as "related factors" in 15% of all fatal crashes
- based on estimates of vehicle miles traveled, the overall nighttime crash rate is approximately 1.6 times that of the daytime rate, while the fatal crash rate is three to four times greater at night

Sullivan, M., Flannagan, M. 1999. Assessing the potential benefit of adaptive headlighting using crash databases. HS-042 899, UMTRI-99-21.
- used 11 years of fatality data to assess the light sensitivity of different scenarios (intersections and curvy roads). Dividing the analysis into day, night, and twilight time zones, they found a seasonal sensitivity to light in the twilight zone

11.2 Characteristics of Lighting and Impact on Vision

Forward lighting on vehicles serves a number of objectives that are to be met simultaneously for the vehicle driver and other roadway users. These include maximizing visual performance (both on-axis and off-axis) and minimizing glare. In order to meet these objectives, lighting systems must be developed with the appropriate characteristics. It is not enough to say simply that a forward lighting system should "provide adequate forward visibility" or "maximize comfort." In order to meet these objectives, specific aspects of lighting can be manipulated. These aspects form the palette of the lighting system designer, and include: spectrum, light output, beam intensity and scene illumination. Additionally, driver characteristics, such as age, must be considered when developing a vehicle forward lighting system. Research has been performed that examines all of these factors.

11.2.1 ON-AXIS AND OFF-AXIS VISION

Baker, H. 1949. The course of foveal light adaptation measured by the threshold intensity increment. Journal of the Optical Society of America 39(2).
- sensitivity is low immediately after the onset of the adapting light; it increases to a maximum several minutes after the onset of the adapting illumination and then declines to an intermediate final level

Bullough J.D., Rea, M. S. 2000. Simulated driving performance and peripheral detection at mesopic and low photopic light levels. Lighting Research and Technology 32(4): 194-198.

- driving performance in terms of speed and on-axis obstacle detection did not depend upon spectrum
- detection of peripheral objects improved for "cooler" or "bluer" light sources relative to "warmer" or "yellower" sources

He, Y., Bierman, A., Rea, M. S. 1998. A system of mesopic photometry. Lighting Research and Technology 30(4): 175.

- peripheral detection response speeds improve for rod-dominated spectra increasingly as light level is reduced
- a model of photometry at mesopic (low, nighttime) light levels is presented to predict peripheral visibility as a function of spectrum

He, Y. Rea M. S., Bierman, A., Bullough, J. 1997. Evaluating light source efficacy under mesopic conditions using reaction times. Journal of the Illuminating Engineering Society 26(1): 125-138.

- off-axis detection (at 15o) improved with a "bluer" spectrum (metal halide) relative to a "yellower" one (high pressure sodium) as light level decreased below 1 cd/m^2
- on-axis detection did not depend on spectrum at any light level

Lingard, R., Rea, M. S. 2002. Off-axis detection at mesopic light levels in a driving context. Journal of the Illuminating Engineering Society 31(1): 33-39.

- detection of peripheral objects from 12° to 29° off axis and with varying contrasts was improved with metal halide illumination relative to high pressure sodium illumination at mesopic light levels

Van Derlofske, J., Bullough, J. D., Hunter, C. M., 2002. Visual benefits of high-intensity discharge forward lighting. Society of Automotive Engineers World Congress, Detroit, MI: Society of Automotive Engineers (Paper 2002-01-0259).

- detection of peripheral targets under typical HID headlamps is improved relative to typical halogen headlamps because of increased peripheral light from HID lamps

Wright, W. D. 1937. The foveal light adaptation process. Proceedings of the Royal Society of London, Series B, Biological Processes 122(827): 220-245.

- the perception of brightness or glare and the performance of some visual tasks do not necessarily use the same visual channels
- it might be possible to design a stimulus to provide good visibility while reducing glare, for example

11.2.2 GLARE

Akashi, Y., Rea, M. S. 2001. The effect of oncoming headlight glare on peripheral detection under a mesopic light level. Progress in Automobile Lighting Symposium, Darmstadt, Germany: Darmstadt University of Technology (pp. 9-22).

- oncoming low beam headlight glare degraded detection performance of a target 23° off-axis but not 15° off-axis

Alferdinck, J. W. A. M., Varkevisser, J. 1991. Discomfort Glare From D1 Headlamps of Different Size, Report IZF 1991 C-21. Soesterberg, Netherlands: TNO Institute for Perception.

- De Boer ratings were highly correlated with glare illuminance
- size (from 0.0006 to 0.15 deg2) had a small influence on rated discomfort (less than 1 De Boer unit total) using the De Boer scale

Anderson, S. J, Holliday, I. E. 1995. Night driving: Effects of glare from vehicle headlights on motion perception. Ophthalmic and Physiological Optics 15(6): 545-551.

- glare from oncoming high beam headlights greatly reduces visual acuity and threshold contrast especially when minor lens opacities are present

Bhise, V. D., Farber, E. I., Saunby, C. S., Troell, G. M., Walunas, J. B., Bernstein, A. 1977. Modeling vision with headlights in a systems context. Society of Automotive Engineers Congress and Exposition, Detroit, MI: Society of Automotive Engineers (Paper 770238).

- regions of acceptable and unacceptable discomfort glare from headlights are bounded by situations giving a De Boer rating of 4 and the conditions created by 110% of the illuminance caused by properly aimed low beam headlights
- previous research is cited that 0.1 lx is an upper limit for the border from non-glaring to glaring conditions (from a comfort perspective)
- four-headlamp systems resulted in more dimming requests than two-headlamp systems having the same glare illuminance
- it was found in field studies that dimming requests from oncoming drivers began to occur when the calculated De Boer rating reached a value of 4 or lower
- depending upon adaptation level, U.S. low beams at the time of the report had corresponding calculated De Boer ratings from 4 to 6, U.S. high beams from 1 to 4, and European ("H4") low beams from 6 to 8; all were calculated for oncoming distances from 400 to 1800 feet
- a model for dimming request prediction is developed that shows the probability of a request as a function of De Boer rating and the exposure time to glare

Bichão, I. C. 1995. Existing glare testers and the evaluation of night driving glare problems. Vision Research 35: S79.

- transient glare affected peripheral detection more than foveal detection
- the difference between transient and steady glare was greater in the periphery

Bichão, I., et al. 1995. Disability glare: effects of temporal characteristic of the glare source and of the visual-field location of the test stimulus, J. Opt. Soc. Am. A 12(10).

- a transient glare source raised threshold by 0.5-0.75 log unit more than a steady glare source, and the transient glare effect was more pronounced and more long lasting in the periphery

Bullough, J. D., Van Derlofske, J., Fay, C. R., Dee, P. 2003. Discomfort glare from headlamps: Interactions among spectrum, control of gaze and background light level. Society of Automotive Engineers World Congress, Detroit, MI: Society of Automotive Engineers (Paper 2003-01-0296).

- a background light level ranging from 0.1 to 3 cd/m^2 did not affect the spectral discomfort response to headlight glare
- a fixed gaze resulted in similar trends for ratings of discomfort as a free gaze

Bullough, J. D., Fu, Z., Van Derlofske, J. 2002. Discomfort and disability glare from halogen and HID headlamp systems. Society of Automotive Engineers World Congress, Detroit, MI: Society of Automotive Engineers (Paper 2002-01-0010).

- De Boer ratings were strongly correlated with glare illuminance (0.04 to 2.6 lx)
- threshold contrast was strongly correlated with glare illuminance
- HID glare sources were consistently rated as more glaring than halogen sources, but less so than blue-filtered halogen sources, although the blue source had higher scotopic content than both the HID and unfiltered halogen sources
- different sources did not result in different threshold contrast once glare illuminance was constant
- De Boer ratings were more highly correlated with glare illuminance calculated using a short-wavelength cone luminous efficiency function

Bullough, J. D., Rea, M. S. 2001. Driving in snow: Effect of headlamp color at mesopic and photopic light levels. In Lighting Technology Developments for Automobiles, SP-1595. Warrendale, PA: Society of Automotive Engineers.

- an analysis of discomfort glare studies relating to street lighting provided initial evidence that rod photoreceptors might play a role in discomfort glare under some conditions

Ferguson, H. M., Reeves, J., Stevens, W. R. 1953. A note on the relative discomfort from mercury, sodium and tungsten light sources. GEC Journal (July).

- low-pressure sodium illumination required a luminance approximately three times that of mercury vapor illumination to appear equally "uncomfortable"

Flannagan, M. J., Sivak, M., Traube, E. C., Kojima, S. 2000. Effects of overall low-beam intensity on seeing distance in the presence of glare. Transportation Human Factors 2(4): 313-330.

- based on visibility alone, there is no obvious upper limit for glare
- however, based on discomfort, subjects find glare objectionable long before it will negatively impact visual performance

Flannagan, M. J., Sivak, M., Battle, D. S., Sato, T., Traube, E. C. 1993. Discomfort Glare from High-Intensity Discharge Headlamps: Effects of Context and Experience, UMTRI-93-10. Ann Arbor, MI: University of Michigan Transportation Research Institute.

- HID headlamps were rated on the De Boer scale as more glaring than halogen headlamps (approximately 50% difference in illuminance to achieve equivalent ratings)
- older drivers gave lower De Boer ratings
- having HID headlamps on one's own vehicle increased De Boer ratings
- for sources with more saturated colors, the order in increasing 'glairiness' is: red, yellow, green, blue

Flannagan, M. J., Sivak, M., Gellatly, A, W., Luoma, J. 1992. A Field Study of Discomfort Glare from High-Intensity Discharge Headlamps, Report UMTRI-92-16. Ann Arbor, MI: University of Michigan Transportation Research Institute.

- glare illuminance from 0.02 to 4.6 lx was strongly correlated with De Boer ratings
- SPD (HID or halogen) significantly impacted De Boer ratings with HID lamps having lower ratings
- for equal De Boer ratings, halogen lamps needed to be more than 50% higher in intensity than HID lamps

Fry, G. A. 1954. Evaluating disability effects of approaching automobile headlights. Highway Research Bulletin (89): 38-42.

- concludes that the effect of disability glare can be predicted by using a veiling luminance concept to capture the impact of scattered light in the eye

Hadden, O. B., Ring, C. P., Morris, A. T., Elder, M. J. 1999. Visual, refractive, and subjective outcomes after photorefractive keratectomy for myopia of 6 to 10 diopters using the Nidek laser. Journal of Cataract and Refractive Surgery 25: 936-942.

- most patients receiving refractive surgery reported no significant night vision problems, some patients reported improvements in night visibility and reduced glare at night

Hare, C. T., Hemion, R. H. 1968. Headlamp Beam Usage on U.S. Highways, Report AR-666. San Antonio, TX: Southwest Research Institute.

- most drivers tended to overdrive their own headlights, even without glare, and more so with glare
- dimming from high to low beams seems to be a function of discomfort, or more likely, the anticipation of discomfort

Irikura, T., et al. 1999. Recovery time of visual acuity after exposure to a glare source. Lighting Res. Technol. 31(2): 57-61.

- the time taken for the recovery of visual acuity after exposure to a glare source with a duration of 1.6 s or less, was determined by visual experiments where the background luminance was set to 0.1 cd/m2 or 0.32 cd/m2
- recovery time increases as the exposure time increases; at every luminance of the glare source, recovery time clearly grows shorter as the background luminance increases
- recovery time is determined by the product of the luminance of the glare source and the exposure time

Lehnert, P. 2001. Disability and discomfort glare under dynamic conditions: The effect of glare stimuli on human vision. Progress in Automobile Lighting Symposium, Darmstadt, Germany: Darmstadt University of Technology (pp. 582-592).

- halogen lamps were used as glare stimuli
- De Boer ratings were highly correlated with glare illuminance (0.1 to 10 lx)
- De Boer ratings were highly correlated with glare duration (0.2 to 10 sec)
- glare illuminance had a greater impact on De Boer ratings than duration

Miles, P. W. 1954. Visual effects of pink glasses, green windshields and glare under night driving conditions. American Medical Association Archives - Ophthalmology 51: 15-23.

- glare is stated to be inversely proportional to the size of the glare source (for the same intensity), and it is proposed that headlights be designed larger in area

Mortimer, R. G., Becker, J. M. 1974. Some operational considerations affecting the performance of current and proposed head-lamp beams. Transportation Research Record (502): 34-40.

- a glare illuminance of 0.1 lx from headlamps is proposed as the point at which discomfort begins

Olson, P. L. 1990 Glare from following vehicles, SAE (Society of Automotive Engineers) Transactions, v 99, n Sect 6, p 237-242

- glare from sources in front of or behind a vehicle can be quite significant; methods of reducing the glare levels are discussed

Olson, P. L., Sivak, M. 1984. Discomfort glare from automobile headlights. Journal of the Illuminating Engineering Society 13(3): 296-303.

- glare illuminance (0.0004 to 6.5 lx in a laboratory study and 0.003 to 11 lx in a field study) was highly correlated with De Boer ratings
- De Boer ratings were higher in the field study than in the laboratory study
- older subjects reported lower De Boer ratings
- authors conclude that estimates of acceptable discomfort glare based on laboratory results might be too conservative

Pohl, W., et al. 2001. Enhancing visibility by reducing glare of street luminaries and headlamps. PAL 2001 Symposium, Darmstadt University of Technology.

- glare from the headlamps of oncoming vehicle is much higher than the glare caused by the street luminaires
- decomposed headlights and streetlights are recommended to use to reduce the glare and the visibility could be increased and the light level could be decreased

Powers, L. D., Solomon, D. 1965. Headlight glare and median width: Three exploratory studies. Highway Research Record (70): 1-28.

- as expected, threshold contrast increased as the amount of glare light increased

Ranney, T. A., Simmons, L. A., Masalonis, A. J. 2000. The immediate effects of glare and electrochromic glare-reducing mirrors in simulated truck driving. Human Factors 42(2): 337-347.

- the presence of glare negatively impacted simulated driving performance in terms of target detection and lane control
- reduction of glare with electrochromic mirrors did not significantly improve performance although subjects preferred the mirrors

Ranney, T. A., Simmons, L. A., Masalonis, A. J. 1999. Prolonged exposure to glare and driving time: Effects on performance in a driving simulator. Accident Analysis and Prevention 31: 601-610.

- intermittent glare presented over two 8-hour sessions reduced performance, but glare did not increasingly impair performance more after 8 hours than it did after shorter periods

Rumar, K. 2001. Intensity of high-beam headlights. Progress in Automobile Lighting Symposium, Darmstadt, Germany: Darmstadt University of Technology (pp. 829-848).

- reference is made to previous research that dimming of one's own high beams occurs when the discomfort from oncoming vehicles is between 4 and 5 on the De Boer scale
- reference is made to previous research that a glare illuminance just higher than 1 lx is the maximum acceptable by drivers

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

- discomfort as measured by the De Boer rating was highly correlated with the logarithm of the glare illuminance (from 0.003 to 20 lx)
- discomfort was reduced at higher background adaptation levels (from 0.015 to 15 cd/m2)
- discomfort was reduced at larger angles from the field of view (from 1 to 20 degrees)
- discomfort from multiple sources was the same as from a single source within the range 1 to 5 degrees and 0.003 to 9.6 lx
- a formula for the predicted De Boer rating is provided for the range of conditions used in the experiments reported

Schreuder, D. A. 1969. Side Lights and Low-Beam Headlights in Built-Up Areas. Voorburg, Netherlands: Institute for Road Safety Research.

- it is stated that without high ambient light levels along roadways provided by fixed lighting, glare from low beams is unacceptably high because the resulting veiling luminance reduces contrast of important objects along the road

Sivak, M., Flannagan, M. J., Miyokawa, T. 2000. A First Look at Visually Aimable and Harmonized Low-Beam Headlamps, Report UMTRI-2000-1. Ann Arbor, MI: University of Michigan Transportation Research Institute.

- visually aimable and harmonized beam lamps tend to result in reduced glare to oncoming drivers, compared with conventional headlamps in the U.S.

Sivak, M., Flannagan, M. J., Traube, E. C., Kojima, S. 1999. The influence of stimulus duration on discomfort glare for persons with and without visual correction. Transportation Human Factors 1(2): 147-158.

- glare illuminance from 0.5 to 8 lx had a strong relationship with De Boer ratings
- glare duration (from 0.125 to 2 sec) also had a correlation with De Boer ratings but less so than illuminance
- subjects with glasses or contact lenses had slightly lower De Boer ratings but the difference was not statistically significant

Sivak, M., Flannagan, M. J. 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.

- the authors challenge the conventional notion that disability glare and discomfort glare are separate phenomena
- nonetheless, experimental results described tended to focus on one or the other aspect

Sivak, M., Flannagan, M., Ensing, M., Simmons, C.J., Discomfort glare is task dependent. International Journal of Vehicle Design, v 12, n 2, 1991, p 152-159

- an increase in the difficulty of a concurrent task resulted in an increase in discomfort glare
- subjects with poorer task performance tended to assign more discomfort to the glare stimuli than subjects with better task performance

Sivak, M., Olson, P. L., Zeltner, K. A. 1989. Effect of prior headlighting experience on ratings of discomfort glare. Human Factors 31(4): 391-395.

- German subjects reported lower De Boer ratings to headlamps than American subjects, presumably because of reduced experience with headlamp glare in Europe

Stiles, W. S., Crawford, B. H. 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.

- the impact of glare on peripheral vision is well predicted by treating the source of glare as a uniform field of brightness that reduces contrast

11.2.3 SPECTRUM

Akashi Y., Rea, M. S. 2002. Peripheral detection while driving under a mesopic light level. Journal of the Illuminating Engineering Society 31(1): 85-94.

- spectral power distribution of roadway lighting affected detection more than one's own headlights

Alpern, M., Ohba, N. 1972. The effects of bleaching and backgrounds on pupil size. Vision Research 12: 943-951.

- the pupil mechanism is dominated by rods and thus has a spectral sensitivity similar to rods

Berman, S. M., Fein, G., Jewett, D.L., Ashford, F. 1993. Luminance-controlled pupil size affects Landolt C task performance. Journal of the Illuminating Engineering Society 22: 150-165.

- identifying the orientation of briefly-flashed (200 ms), low-contrast letter-c-shaped targets improved slightly under blue illumination relative to red-pink illumination

Bouma, P. J. 1936. The problem of glare in highway lighting. Philips Technical Review 1: 225-229.

- discomfort glare was stated to be caused more by blue than by yellow light

Bullough, J. D., Boyce, P. R., Bierman, A., Hunter, C. M., Conway, K. M., Nakata, A., Figueiro, M. G. 2001. Traffic signal luminance and visual discomfort at night. Transportation Research Record (1754): 42-47.

- red and green sources were rated more uncomfortable to view than yellow sources of equal intensity

De Boer, J. B., van Heemskerck, Veeckens J. F. T. 1955. Observations on discomfort glare in street lighting. Proceedings of the CIE, Zurich.

- illumination from yellow-filtered incandescent street lighting needed to be about 25% higher than from unfiltered incandescent lighting in order to be considered equally uncomfortable by observers

Flannagan, M. J. 1999. Subjective and Objective Aspects of Headlamp Glare: Effects of Size and Spectral Power Distribution, Report UMTRI-99-36. Ann Arbor, MI: University of Michigan Transportation Research Institute.

- glare illuminance from about 1 to 4 lx had a strong relationship with De Boer ratings and with threshold contrast of a visual target
- SPD (halogen versus HID) did not impact disability glare but did impact De Boer ratings, with lower ratings for the HID glare sources
- size (0.3 or 0.6 deg) did not impact either disability or discomfort glare

Flannagan, M., Sivak, M., Ensing, M., Simmons, C. J. 1989. Effect of Wavelength on Discomfort Glare from Monochromatic Sources, Report UMTRI-89-30. Ann Arbor, MI: University of Michigan Transportation Research Institute.

- six wavelengths (480, 505, 550, 577, 600 and 650 nm) were presented at four light levels
- De Boer ratings were highly correlated with glare illuminance (0.03 to 3 lx)
- older subjects gave lower De Boer ratings
- 577 and 600 nm sources were least glaring; 480 and 505 nm sources were most glaring

Jehu, V. J. 1954. A comparison of yellow and white headlamp beams. Light and Lighting 4(10): 287-291.

- no disability glare differences were found between white and yellow headlamps
- subjects preferred to drive with white headlamps, but preferred to see yellow oncoming headlamps

Schreuder, D. A. 1976. White or Yellow Lights for Vehicle Head-Lamps? Voorburg, Netherlands: Institute for Road Safety Research.

- literature on SPD of headlamps is reviewed supporting small benefits of yellower sources for discomfort glare but no appreciable differences for forward visibility or disability glare

Van Derlofske, J., Bullough, J. D. 2003. Spectral effects of high-intensity discharge automotive forward lighting on visual performance. SAE 2003-01-0559.

- the spectral distribution of HID headlamps produces a small, but measurable, improvement over halogen systems for off-axis visual performance
- 'cooler' sources can significantly increase the effectiveness of the light, and 'warmer' sources can decrease effectiveness

11.2.4 LIGHT OUTPUT, INTENSITY AND ILLUMINATION

Bergström, S. 1963. Visible distances during night driving. In Lighting Problems in Highway Traffic, Vol. 2. New York, NY: Pergamon Press.

- seeing distance increased with high beams against high beams over that obtained with low against low beams

Dickinson, H. C. 1931. Report on vehicle and highway mechanics as related to traffic: Headlighting. Highway Research Board Proceedings (11): 388-409.

- concludes that visibility with low versus low beams and high versus high beams is equivalent, with small benefits for right shoulder viewing obtained in the low beam case

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

- intensity requirements were largely independent of observer attributes, the luminance of the road surface and its surrounds and the number and movement of the vehicles
- the results suggest that conspicuity and brightness are different attributes of a light; while both increased with increasing luminous intensity, the observers found that, for a given intensity, a larger source was more conspicuous but that a smaller source caused more discomfort
- optimum lighting appears to be a town beam, based on dimming the present dipped headlight, giving a straight ahead intensity of 80 cd

Hemion, R. H. 1969. Night Visibility Improvement Through Headlight Glare Reduction, Report AR-696. San Antonio, TX: Southwest Research Institute.

- "safe" driving speeds were computed to be higher when using high beams with opposing high beams than when using low beams against low beams

Kosmatka, W. J. 1995. Obstacle Detection Rationale for Vehicle Headlamps, J. of the illuminating Engineering Soc., 24, 36-40.

Kosmatka, W. J. 1997. Comparison of models for detection of highway Obstacles With Headlamps (SAE #970911) Warrendale PA: Soc. of Automotive Engineers.

Kosmatka, W. J. 2003. Differences in Detection of Pedestrians Attributable to Beam Patterns and Speeds, Proceedings of the 5th International Symposium on Progress in Automobile Lighting, (pp 549-566), Darmstadt, Germany, Darmstadt University of Technology.

Mortimer, R.G. 1969. Requirements for automobile exterior lighting. In Visual Factors in Transportation Systems. Washington, DC: National Academy of Sciences.

- research showing that reductions in visibility distance are correlated with the logarithm of glare illuminance at the eye is discussed
- use of a spot lamp to increase forward illumination did not seem to increase glare to oncoming drivers as evidenced by headlight dimming requests

Mortimer, R.G. 1965. The effect of glare in simulated night driving. Highway Research Record (70): 57-62.

- glare illuminance (3 or 9 lx) negatively impacted simulated driving performance but 9 lx was not statistically significantly worse than 3 lx
- duration of glare (7 or 15 sec) did affect performance under some conditions
- frequency of glare (once, twice or four times per min.) did not significantly affect performance
- forward light level affected performance, and it is concluded that headlamp illumination might be increased to improve forward visibility without making glare problems worse

Schwab, R.N., Hemion, R. H. 1971. Improvement of visibility for night driving. Highway Research Record (377): 1-23.

- a correlation between disability glare and subjective ratings of discomfort was found
- no strong relationship between glare and fatigue (performance reduction over longer periods of time) was identified

Schwab, R. 1965. Night visibility for opposing drivers with high and low headlight beams. Highway Research Record (70): 87-88.

- it is concluded that the amount of forward light from headlights, which determines adaptation level, is the primary determinant of visibility and that glare is less important; higher intensities would increase glare but also adaptation and still result in net visibility gains

Van Derlofske, J., et al. Visual benefit of HID automotive forward lighting. SAE 2002-01-0259.

- it was found that, HID headlamps producing SAE beam patterns do produce greater off-axis visual performance than traditional halogen systems due to their increased light output and SPD; the difference depends on the off-axis angle and the beam pattern

Van Derlofske, J., Bullough, J. D, Hunter, C. M. 2001. Evaluation of high-intensity discharge automotive forward lighting. Society of Automotive Engineers World Congress, Detroit, MI: Society of Automotive Engineers (Paper 2001-01-0298).

- HID headlamps produce similar amounts of light as halogen headlamps in the center of the beam pattern, but much more light in the beam periphery
- the light distribution leads to shorter response times to peripheral targets

11.2.5 DRIVER AGE EFFECTS

Chrysler, S. T., Danielson, S. M., Kirby, V. M. 1996. Age differences in visual abilities in nighttime driving field conditions Proceedings of the Human Factors and Ergonomics Society, v 2, p 923-927.

- older drivers' legibility distances were 65% those of the younger drivers
- age differences in the object detection task ranged from a 20% to a 45% reduction for older drivers across visibility conditions

Bennett, C. A. The demographic variables of discomfort glare, IERI project 102.
- older people are more sensitive to discomfort from overly bright lighting systems than young people
- the average population is more sensitive in direct proportion to their age from the 20s to the 70s

Decarlo, D. K., Scilley, K., Wells, J. Owsley, C. 2003. Driving habits and health-related quality of life in patients with age-related maculopathy, Optometry and Vision Science, v 80, n 3, Mar 1, p 207-213.
- questionnaires were administered via telephone interview to 126 patients with age-related maculopathy
- over 50% of drivers reported that because of their vision, they had difficulty with or did not drive at all in rain, at night, on freeways or interstate highways, in heavy traffic areas, or during rush hour

Keskinen, E., Ota, H., Katila, A. 1998. Older drivers fail in intersections: speed discrepancies between older and younger male drivers, Accident Analysis and Prevention, v 30, n 3, May, 1998, p 323-330.
- a high percentage of older drivers' accidents occur at intersections
- the problems may be in perception or attention, motor performance or inadequate interaction with other road users

Schmitz, S., Dick, H. B., Krummenauer, F., Schwenn, O., Krist, R. 2000. Contrast sensitivity and glare disability by halogen light after monofocal and multifocal lens implantation. British Journal of Ophthalmology 84(10): 1109-1112.
- older subjects with different types of lens implants did not experience glare to different degrees; contrast threshold in the presence of glare was the same in both groups

Theeuwes, J., Alferdinck, J. W. A. W. 1996. The Relation Between Discomfort Glare and Driving Behavior, Report DOT HS 808 452. Soesterberg, Netherlands: TNO Human Factors Research Institute.
- actual driving in the field was performed
- glare illuminance from 0.28 to 1.1 lx from rig mounted sources (halogen SPD)
- De Boer ratings less 'glaring' than predicted by Schmidt-Clausen and Bindels (1974) but depended on task difficulty
- De Boer ratings correlated with willingness to look into glare source (e.g., to see a turn signal)
- older drivers gave higher De Boer ratings
- European and American drivers gave equivalent De Boer ratings
- 0.55 and 1.1 lx impaired driving performance about equally (detection of targets and distance at which they were detected), and older drivers performed worse, despite higher De Boer ratings

Tsongos, N. G., Schwab, R. N. 1970. Driver judgments as influenced by vehicular lighting at intersections. Highway Research Record (336): 21-32.
- older drivers reported lower discomfort from oncoming headlights than younger drivers

11.3 Technical Aspects of Forward Lighting

11.3.1 FORWARD LIGHTING TASK AND DESIGN GOALS

Ideally, all forward lighting devices would provide illumination values similar to daylight without causing glare for other road users. This goal is technically impossible today and will probably remain so for many years yet to come. Research studies may give us some insight about the road to improvement.

Anon. Vehicle Lighting Design for Optical Visibility and Performance, SAE Special Publications, n 857, Feb, 1991, Vehicle Lighting Design for Optical Visibility and Performance, 92p.

- driver performance is discussed in terms of reaction times to brake lamps; other topics covered include: electrochromic mirrors, driver confidence, curved reflectors for headlamps, light distributions, fog lamps, dipped beam patterns, and brake lamps

11.3.2 Headlamp Beam Patterns

The design of lower (passing) beam headlamps has always been one of the more difficult tasks for optical engineers over the years. Achieving a "proper" balance between glare and seeing distance, along with knowing what that balance should be, is not a trite problem. Regional differences in specifications, available technology, and personal inclinations have led to many different ideas about what does and does not constitute acceptable performance. This is still a difficult question, even today. In contrast, it has been relatively simple to find agreement about upper (driving) beam and front fog lamp characteristics. Perhaps continuing research will lead to a world wide consensus about what constitutes the best performance possible for all road illumination devices.

Sivak, M., 2002. Performance of the first generation of HID headlamps in the U.S., the University of Michigan, Transportation Research Institute, Report No. UMTRI-2002-14.

- HID lamps produced more light on all parts of the beam pattern except for a central area near the horizontal, and an area above the horizontal in the far left periphery

11.3.3 Headlamp Mounting Height

Headlamp mounting height has a definite effect on what may be achieved in the balance between glare and visibility. Acceptable characteristics may only be achieved within a certain range of heights. Recent efforts in the field have helped to refine those boundaries.

Headlamp Mounting Height Task Force, 27 November 2000 Draft.

- near-foveal eye point illuminance levels of 3 to 4 lx for short duration were found
- for longer periods of time, the discomfort glare tolerance decreases to the range of 1.5 to 3 lx
- apparent tolerance in the peripheral areas of vision is greater by a 3.24-times-factor
- the task force determined side mirror illuminance limits of 10 to 20 lx
- a rapid increase in glare begins at about a 10 cm height differential from reference
- maximum headlamp mounting height should include the 85th percentile driver

11.3.4 Headlamp Leveling

It has long been known from static testing that an excellent headlamp aimed poorly will not perform as well as an average headlamp aimed accurately. However, even the best designed and well maintained system has suffered from aim variation due to vehicle loading and road contours in actual usage. The development of headlamp leveling systems offers the potential to keep lamps aimed properly in relation to the road surface over a large range of loading and road variables.

Harris, A. J. 1953. The meeting beams of headlights: Effects of deterioration and misaim. Illuminating Engineering Society Transactions 18(8): 207-220.

- visibility in the presence of a stationary glare source is found to be the same as that in the presence of a moving glare source

Rumar, K. 1965. Visibility distances in night driving with misaligned meeting dipped headlights, Department of Psychology, University of Uppsala, Sweden, Report 28.

- compared to correctly adjusted meeting lights, the visible distance was not increased, or at least noting worth mentioning, by a downward misalignment of meeting headlights, while on the other hand an upward misalignment of 1-2 degrees of meeting headlights decreased the "normal" visible distance by about 25%

11.3.5 HEADLAMP CLEANING

Dirt build-up on headlamps has been a concern to drivers since the early days of motor vehicles and the need to be on the road at night. It has only been in the last two decades that dirt has been recognized as a source of glare for oncoming drivers as well as reduced visibility to the driver. With the advances in bulb technology resulting in much higher outputs, maintaining low levels of dirt and snow buildup on lamps is even more critical. This has lead to the development of systems to clean and wash the headlamp.

Alferdinck, J. W. A. M., Padmos, P. 1988. Car headlamps: Influence of dirt, age and poor aim on glare and illumination intensities. Lighting Research and Technology 20(4): 195-198.

- headlamps on many vehicles were found to be misaimed and dirty, increasing glare illuminance to other drivers and reducing one's own forward illuminance

Rumar, K. 1973. Dirty Headlights – frequency and visibility effects, Department of Psychology, University of Uppsala, Sweden, Report 136, 1973.

- even in dry weather on seemingly clean roads, light reduction is normally 10-20%
- in bad (slushy) road conditions few cars have light reduction below 50%
- drivers normally do not react to light reduction below 60%
- 60% light reduction causes a 20% reduction of high beam visibility and a 15% reduction of low beam visibility

11.3.6 AFS HEADLAMPS

AFS or Advanced Front Lighting Systems is a modern, hi-tech forward lighting system for vehicles that has its founding in the swivel headlamps of some of the early 20th century motor cars. The modern AFS headlamps not only incorporate mechanical swivel headlamps into these systems but many other lamps and bulbs and an array of sensors and actuators to adapt the forward lighting of a vehicle to a variety of road and environmental conditions. These modern AFS systems can accept inputs from the sensors to adjust the lighting for type of road, weather conditions, vehicle attitude, wheel position, and road environment (type or location) to adjust the front lamps to optimize lighting thus improving safety.

Adler, B., Lunenfeld, H. Evaluation of a three-beam vehicle lighting system, Transportation Research Record 502, pp.22-33, 1974.

- one new-term improvement for vehicle forward lighting is a 3-beam 4-head-lamp system: High beam, low beam and midbeam
- a computer program calculated the glare in the rearview mirror as a following vehicle with different headlighting system approached from the rear and evaluated the 4 modes achieved by combining the 3-phase beams

- the results shows very minor difference in glare among any of the beam configurations on the Tame mode. The equation used for the glare evaluation is E = K (candela output * reflectivity) / (oblique distance)^2
- the high-beam mode using all 4 head lamps appears to be the best configuration because it doesn't represent excessive glare and doesn't yield greater dimming requests, but does yield greater seeing distance

Birch, S. 2001. Adaptive front lighting, aei December. PP.39-42.

- VARILIS program was introduced and its aim is to enhance the lighting performance via a clearer definition of the cutoff in terms of sharpness and geometry of the light, reduction of illuminance in the area in front of vehicle and a reduction of self-glare
- the paper describes Hella's AFS concept—five principle lighting functions-- as the following:
  - Town light: a symmetric cutoff, wide scatter and homogeneity across the entire area of illumination
  - Country light: recognition of the course of the road, recognition of objects in the vicinity of the road, guidance of the driver's attention to relevant areas of the road and low level of dazzle to other road users
  - Motorway type light: provide the driver with greatest range of vision while dazzling the traffic in front as little as possible. A symmetrical beam pattern with a sharp cutoff and very small forward rake angle is the best approach
  - Adverse weather light: provide the driver with good illumination and guidance by producing a high intensity of light in the distant zone at the outward edge of the road, illuminate the width of the road (with orientation on the right hand or left hand side of the road) and reduce the level of illumination in the immediate frontal zone—up to about 20m in front of the vehicle—to keep reflection glare to oncoming traffic down to an acceptable level
  - Bending light: static bending light—a headlight on one side is switched on and/or increased in brightness. Dynamic bending light—produced by swiveling the whole beam according to the radius of the curve either on both sides of the car or the inner lamp to the curve

Damasky, J. and Huhn, W. 1997. Variable Headlamp Beam Pattern – Lighting Requirements for Different Driving Situations. SAE technical paper #970647.

- addressed beam patterns for urban roads, country roads, and motorways
- to determine appropriate beam patterns for those road types, the authors first videotaped forward roadway views and analyzed potential positions of important targets such as traffic signs, delineation reflectors, and proceeding cars
- based on the probability of emergence of those targets for each roadway type, a minimal illuminance requirement was determined

Diem, C. 2003. Different control parameters of the bending light function-influence on the driver. PAL 2003 vol. 10, p.231-241.

- conducted a field test comparing three variations of a bending beam system by using subjective brightness and overall acceptance evaluations and eye movement analysis
- the three variations were a standard headlamp system, a one-sided swivel system, and a parallel symmetric swivel system
- the results confirmed that eye fixation was a function of illumination distribution

Diem, C. et al. 1999. Analysis of eye movement behavior using movable headlamps. PAL vol.5, p.185-207.

- investigated eye movement of drivers with bending lights and standard headlamps using an eye-tracking system and a test track (straight and 110 m radius curve, no other cars)
- compared a standard halogen, a halogen AFS, and an HID AFS headlight system
- the data showed that the standard HID system resulted in 30.9m and 38.5m for left and right-hand curves respectively, whereas the AFS HID system resulted in 35.8m and 43.5m for left and right-hand curves respectively

Dietz. 1997. Scattering luminances in fog analyzed by a simulation software. PAL vol.2, p.151-156.

- this study calculated fog luminance caused by a headlamp system using a calculation tool of fog luminance developed by Boehlaw-Godau and Rosenhahn (1995) based on the Monte-Carlo method
- calculations compared headlamp location (left and right), different mounting heights, and different fog densities

Frieding, A. 1999. Optimized headlamps for wet road conditions. PAL 1999 vol.5, p.307-315.

- calculated maximum acceptable road luminance under various pavement conditions, from dry to wet
- under wet conditions, reduced luminance (25% and 50% of the dry) in the central roadway zone was still deemed “acceptable”, purportedly due to decreased adaptation luminance. However, on side lane markers for orientation, desired luminance was increased to 180% on the left and 220% on the right
- evaluations took place on 80 km of country road, federal highway, and motorway

Grimm, M. 2001. Improved nighttime visibility for drivers through dynamic bend lighting. PAL 2001 vol. 8, p.339-347.

- tested target (40 cm x 40 cm, reflectance = 0.08) visibility as a function of curve radius using a prototype dynamic bending beam
- for a right-hand curve, the dynamic bending beam increased object visibility. For r = 200 m, swivel system detection distance (d) = 82 m, and standard system d = 52 m; for r = 400 m, swivel system d = 84 m, and standard system d = 61 m; for r = 1300 m, detection distances for both systems were nearly equal
- experiment methodology used a moving target for detection and stationary drivers

Hamm, M. 2002. Adaptive lighting functions history and future-- performance investigations and field test for user’s acceptance. SAE technical paper #2002-01-0526.

- conducted a field test to collect subjective evaluations of visibility with an AFS experimental system
- a parallel asymmetric swivel system was rated as most satisfactory in terms of visibility, followed by the parallel symmetric swivel. The one-sided swivel though rated as the least satisfactory, was still considered to provide adequate illumination

Hamm, M., Rosenhahn, E., and Rosenhahn, E., Hamm, M. 2001. System strategies and technology for improved safety and comfort with adaptive headlamps.

- evaluated the feasibility of AFS using prototypes, using target detection distance (20 cm x 20 cm ρ = 0.1) placed on the right edge of a curve (r = 250 m) and subjective comfort evaluations as criteria
- the visibility with the HID AFS system gains an earlier detection time of 1.9 s
- the results of the subjective evaluations showed that the AFS was more positively rated than an HID system
- the authors also compared two sensor systems. One sensor system controlled the angle of the bend through steering wheel angle, and lateral acceleration. The other system was a prediction system using a video sensor and a steering wheel angle sensor. The prediction system always provided the best results for target detection along a curve, especially at the entrance of the curve

Hara, et al. 2001. Evaluation of AFS from driver's point of view. PAL 2001 vol.8, p.397-402.

- the authors evaluated a standard halogen headlamp system and an AFS halogen headlamp system (no further details provided)
- through eye fixation analysis using an eye mark recorder (EMR-8), they found that eye fixation was not always dictated by light distribution

Hogrefe, H. 2000. Adaptive front lighting systems for optimum illumination of curved roads, highway lanes and other driving situations. SAE technical paper #2000-01-0431.

- evaluated three types of bending beams: two static beams, and a combination of a static and a dynamic beams through an in-house subjective evaluation (no data available)
- the systems comprised of static beams alone performed worse, in terms of forward visibility, than the system utilizing the combination movable and static beam. The authors conclude that the static component is beneficial to AFS. The static component is able to illuminate curves of small radii and intersections better than the dynamic bending light alone. When the dynamic beam alone was the source of illumination, the larger angular rotation required for curves of small radii resulted in a period of time when illumination is reduced in the central direction. However, the dynamic component was necessary to illuminate curves of larger radii

Hogrefe, H., Neumann, R. 1997. Adaptive Light Pattern – A New Way to Improve Light Quality. SAE technical paper #970644.

- reviewed AFS concepts. Town, country, motorway beam patterns explained
- beam pattern changing technology reviewed, and controls: a distinction is made between direct automatic control and more sophisticated predictive controls

Ikegaya, M., Ohkawa, M. 2003. Study of distribution control methods for AFS. PAL 2003 vol. 10, p.426-439.

- specifically addressed the bending function's ability to illuminate an S-curve (a right-hand curve turning into a left-hand curve)
- two evaluations: a computer simulation-based illuminance calculation and a field test to measure detection distance of a target (20 cm x 20 cm ρ =0.05)
- three systems compared: a standard system, a one-sided swivel system (ά and 0°), a parallel symmetric swivel system (ά and ά), and a parallel-asymmetric swivel system (ά and ά /2)

Ishiguro, K., Yamada, Y. 2004. Control technology for bending mode AFS. SAE technical paper #2004-01-0441.

- looked at eye fixation during daytime and nighttime for a dynamic bending headlamp system. The authors also investigated the effect of vehicle speed on eye fixation behavior
- scenarios: Test course with curve radii ranging from 20-250m; vehicle speeds of 30, 45, 60 km/h

JARI. 2001. Japan Automobile Research Institute's report on research commissioned by the Japan Automobile Manufacturers Association-Research on AFS (second year of three year project).

- calculated illuminance profiles for three 3 bending systems (standard non-AFS, one-sided bending, symmetrical two-sided bending) on 4 curve scenarios (right-hand, left-hand, and left and right S-curves). Computer-generated illuminance calculations were conducted for the road edge, driving land center, and center line, and were computer generated. Parallel swivel system provided up to ½ log unit more light than standard
- glare was evaluated through computer simulations, as well as a field test, which determined oncoming drivers' eye position. The principle conclusion set forth by the authors is that swiveling of the headlamps does not result in an induced line of vision. The authors also note that when entering a curve the driver's gaze followed the curve quicker than the swivel system could operate

Kalze, J. 2001. Hella KG Hueck &Co., German, Situation adapted light distributions for AFS-Headlamps, PAL 2001, pp.474-484.

- Hella's concept for AFS was summarized, the headlamp system is composed of a basic light module (left and right headlamp), high beam, and static bending light to provide a comfortable compromise between visibility distance, reduced glare to oncoming traffic, and illuminance uniformity
- 5 kinds of lighting functions: Town light, Country light, Motorway light, Adverse weather light and Static and dynamic bending light.
- in TL, the basic light modules(left and right VarioX-modules) provide a symmetrical cut-off-line geometry. Depending on the momentary speed, the modules are swiveled in divergent mode
- for AL, in a typical night rain situation, the left basic light model (VarioX-module) generates a horizontal cut-off-line and is forced into divergent mode with an angle of 15 degree. This ensures high visibility distance on drivers lane and reduces reflex glare for the oncoming traffic
- for AL, in a heavy wet situation, both VarioX-modules generate a horizontal cut-off-line and go into the maximum divergent mode (30 degree), this beam pattern is similar with TL
- for AL, in a heavy fog situation, both VarioX-modules generate the motorway beam pattern, go into divergent beam orientation and are leveled downwards

Kalze, F-J. 1999. Static bending light - A new light function for modern headlamp system, 1999 SAE.

- the side area close to a car up to a distance 20-30 m, called "No man's land", is illuminated by a new light function called static banding light
- computer software - LDE was used to simulate and analysis the new light distribution

Kobayashi, et al. 1999. Development of the Phase-I AFS front lighting system. PAL 1999 vol.5, p.449-464.

- addressed appropriate beam distributions based on a stopping distance calculation. Based on the analyses, the authors proposed forward lighting requirements for AFS functions including motorway light, country light, town light, and bending light

- the authors also evaluated an AFS prototype; each headlamp unit was composed of one main HID headlamp (which rotated) and three additional static bend headlamps. Speed and steering sensors controlled the degree of rotation. Various combinations of the four beam systems were compared in visibility tests with a standard halogen headlamp system. The results of the evaluation indicated substantial improvement over traditional headlamp systems

Kobayashi, et al. 1997. Development of new forward lighting systems with controllable beams, SAE Special Publications, v 1249, New Concepts in International Automotive Lighting Technology, 970646, p. 19-35

- new forward lighting system has been developed. This system controls and adjusts to optimum settings headlamp and fog lamp system beams and beam patterns, based on data collected by onboard sensors which are either currently incorporated in vehicles, or are comparatively easy to develop. Through beam optimization control, this system aims to radically improve nighttime driving safety and comfort
- the low beams of this forward lighting system enable independent control of the oncoming vehicle and forward vehicle side cut off line in a range of +1.5° to -0.5°. The high beam system enables control of the irradiation angle to a maximum of 6°. The fog lamp system allows control of the beam pattern side irradiation in a range of 30° to 50° toward the road shoulder.
- illuminance values were measured at a distance of 100m from the vehicle with the light source. de Boer ratings were calculated assuming an adaptation luminance of 1 cd/m^2. Calculated de Boer ratings were above the 'just acceptable' (rating of 4) except for one condition when the HID prototype was elevated such that the cut-off (assume Japanese beam pattern) was raised 1.5 degrees

Kobayashi, Hayakawa. 1991. Beam controllable headlighting systems. SAE technical paper #910829.

- discussed AFS prototypes and control algorithm. This study also conducted a photometrical analysis on the system performance in terms of illuminance distribution. This study concluded visibility along a curve would be enhanced by the bending light. No visibility tests were performed

Kormanyos, C. M. 1998. HID system with adaptive vertical aim control ,SAE Special Publications, v 1323, Feb, 980003, Automotive Lighting Technology, p 13-18.

- a high intensity gas discharge headlight with integrated adaptive vertical aim control is described that provides improved driving, comfort and safety and also reduces glare for oncoming drivers by maintaining optimal vertical adjustment of the headlight beam during varying driving situations

Manassero, G. et al. 1998. Adaptive headlamp: a contribution for design and development of motorway light. SAE technical paper #980010.

- conducted a fundamental study to determine appropriate beam distribution in terms of contrast sensitivity using target detection methodology

McLaughlin, S., Hankey, J., Green, C. Larsen, M. 2003. Discomfort glare ratings of swiveling HID headlamps. USG No. 3774. General Motors North America.

- investigated the discomfort glare imparted to oncoming drivers by comparing a standard HID headlamp system with a swivel HID headlamp system. The authors performed statistical analysis

Miura, J., Ito, M., Shirai, Y. 1997. Three-level control architecture for autonomous vehicle driving in a dynamic and uncertain traffic environment, IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC, p 706-711.

- this paper proposes a novel control architecture for autonomous vehicle driving in a dynamic and uncertain traffic environment. The architecture is composed of three levels: (1) the operational level deals with a reactive control of a vehicle in a short time cycle; (2) the tactical level decides proper maneuvers based on prediction of future states using probabilistic traffic models; (3) the meta-tactical level, which is the feature of the architecture, timely activates an appropriate tactical-level planning procedure according to both the history of maneuvers and the current traffic condition.
- a utility-based maneuver evaluation method is also described. The proposed architecture was tested on a highway driving simulator in various traffic scenarios; simulation results show the feasibility of the architecture

Neumann, R. 2003. Advanced front lighting system with halogen bulb concept-safety improvements for everybody. PAL 2003 vol. 10, p.715-722.

- proposed an inexpensive AFS solution using halogen headlamps instead of HID headlamps. A field experiment measured recognition distances of targets on a test track. The study indicated that as target detection became more difficult, the relative effectiveness of the halogen-AFS system increased. The results also suggested that, with the halogen-AFS system, drivers could detect pedestrians 1.8m earlier than with the standard halogen system. This study concluded that the halogen-AFS system can improve visibility by 55% in relation to the standard halogen system. In relation to a standard HID system, the halogen-AFS system demonstrated an improvement in visibility of 23%.
- targets were designated as easy to see 'E' (located at straightforward sections), moderate to see 'M' (located at the inside and outside bends of moderate curves) and hard to see 'H' (located at the inside bends of narrow curves); while driving, subjects indicated through a signal that they detected the target. The results were given as the percentage of targets correctly detected. The results for: Target type E were, 71% and 84%, for standard halogen system and halogen-AFS system respectively; for target type M were 68% and 85%, For standard halogen system and halogen-AFS system respectively; for target type H were 46% and 72%, for standard halogen system and halogen-AFS system respectively
- the author also performed a test which asked subjects to stop the vehicle when a dummy (mimicking a pedestrian) became visible. While approaching a curve (no radius given) as the test vehicle passed a photosensor trigger, a dummy was simultaneously brought onto the roadway. The vehicle's speed while approaching the curve was set at 50 km/h. Driver reaction time for braking was measured. The measurements show that dummy detection occurred 1.8m earlier with the AFS system vs. the standard system (11.3 m and 13.1 m for the standard system and the AFS system respectively)

Rosenhahn, E. O. 2001. Adaptive Headlamp Systems Concerning Adverse Weather: Fog. PAL 2001 vol. 9.

- calculated fog luminance distribution under various conditions, and subjective evaluations
- the author proposed a recommendation for fog light adjusted according to fog density

Rosenhahn, E.O. (1999). Headlamp Components for Adaptive Front lighting— Usability of a Lighting Function for Adverse Weather Conditions. PAL 1999 vol. 6, p.677-688.

- measured/calculated glare illuminance and threshold luminance for HID and halogen headlamps in wet road conditions for a wide range of distances