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TABLE OF CONTENTS

1.	SCOPE.....	3
2.	REFERENCES.....	3
3.	INTRODUCTION.....	3
3.1	Responses to Lighting.....	3
3.2	Characteristics of Lighting.....	3
3.3	Research Methods.....	4
4.	INTENSITY AND ILLUMINANCE	4
4.1	Analytical Methods	4
4.2	Laboratory and Field Methods	4
5.	AIM AND SHAPE OF BEAM PATTERN.....	5
5.1	Analytical Methods	5
5.2	Laboratory and Field Methods	5
6.	LOCATION AND MOUNTING HEIGHT	5
6.1	Analytical Methods	5
6.2	Laboratory and Field Methods	5
7.	DIRT, WATER, AND HEADLIGHT AGE.....	6
7.1	Analytical Methods	6
7.2	Laboratory and Field Study Methods.....	6
8.	SPECTRAL POWER DISTRIBUTION	6
8.1	Analytical Methods	6
8.2	Laboratory and Field Methods	6

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Documents

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9.	SYSTEM LIFE AND RELIABILITY	7
9.1	Analytical Methods	7
9.2	Laboratory and Field Methods	7
10.	DISCUSSION	7
11.	INFORMATIVE REFERENCES	7
11.1	Importance of Lighting	7
11.1.1	Lighting, Visibility, and Crashes	7
11.1.2	Crash Statistics	9
11.2	Characteristics of Lighting and Impact on Vision	9
11.2.1	On-Axis and Off-Axis Vision	10
11.2.2	Glare and Flicker	11
11.2.3	Spectrum	17
11.2.4	Light Output, Intensity, and Illumination	19
11.2.5	Driver Age Effects	21
11.3	Technical Aspects of Forward Lighting	22
11.3.1	Forward Lighting Task and Design Goals	22
11.3.2	Headlamp Beam Patterns	23
11.3.3	Headlamp Mounting Height	24
11.3.4	Headlamp Aim and Leveling	24
11.3.5	Headlamp Cleaning, Degradation, and Headlamp Lens Aging	25
11.3.6	AFS and ADB Headlamps	26
11.3.7	Lighting on Trucks and Buses	37
11.3.8	Lighting on Motorcycles	37
11.4	Light Source Technology	37
11.4.1	Halogen Sources	37
11.4.2	Xenon Gas Discharge—or High-Intensity Discharge (HID)—Light Sources	38
11.4.3	LED and Laser Light Sources	38
11.4.4	Distributive Lighting, Fiber Optics, and Light Pipes	39
11.5	Roadway Lighting Systems	39
11.5.1	System Interaction and Optimization	40
11.6	Regional Differences	40
11.6.1	U.S. Beam Patterns in Comparison to European and Japanese Patterns	40
12.	NOTES	41
12.1	Revision Indicator	41

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 nighttime 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 cannot 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 several 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, including highway signs, pavement and vehicle markings and other reflective elements.
- 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 (intelligent/adaptive lighting).
- 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. This model has been successfully applied to driver visual response data as well as to nighttime crash frequency data (Bullough and Radetsky, 2014). 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 agree 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 found to exhibit excellent agreement with field studies comparing different forward lighting configurations (Eklund et al., 1997).

5. AIM AND SHAPE OF 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 (e.g., Schoettle et al., 2001) provide useful analytical tools for estimating typical forward lighting configurations on the road. Recent data have been published for halogen and light-emitting diode (LED) headlights (Flannagan, 2019) and inspection of these data has indicated that newer headlights in the U.S., for example, produce less illumination on traffic signs than those produced 10 years before (Larkin, 2020). 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. Software models have also been developed and used to evaluate the performance of headlight beam patterns (e.g., Flannagan et al., 2009). 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). As the impact of headlamp aim on visual effectiveness grows clearer, studies to assess the vertical aim status of headlamps in the field have been undertaken to understand the prevalence (Skinner et al., 2009) and impact (Bullough, 2016) of poor headlamp aim. Akashi et al. (2008) applied various analytical techniques to headlamp photometric data to assess visibility and glare impacts of headlamp characteristics such as visual aiming type, optical type, and light source type.

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. Akashi et al. (2008) evaluated glare from headlamps mounted at different mounting heights to confirm the role of headlights on pickup trucks and sport utility vehicles as a factor in increased complaints about glare.

7. DIRT, WATER, AND HEADLIGHT AGE

7.1 Analytical Methods

Few studies, if any, have provided tools for calculating or predicting the impact of dirt, water, and headlight age on forward lighting system performance. One exception is a calculation tool described by Chang et al. (2008), which can be used to estimate how long lens condensation takes to clear under different temperature and humidity conditions.

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 and condensation. 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; refer to 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.

The American Automobile Association (AAA, 2018) recently performed measurements of new, degraded, and restored headlights from various automobile models and found that lens hazing and yellowing from age, pollution and abrasion significantly reduced light output and changed the resulting light distribution. Even do-it-yourself restoration techniques were helpful in bringing the beam performance closer to its original performance, although none of the techniques totally restored performance to its initial level.

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. More recently, the Illuminating Engineering Society (2015) has developed a "fidelity" metric that is very similar to CRI, and a gamut metric that is based on gamut area but based on 99 spectral reflectance curves rather than the eight curves used for CRI.

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 considers 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. The publication of a model and system of mesopic photometry incorporating the influence of spectrum on visual performance (CIE, 2010) provided a useful analytical tool.

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). These findings also apply to newer headlamp technologies using light emitting diodes (LEDs); LED sources with higher correlated color temperature (CCT) will be judged as more glaring (Sivak et al., 2005; Nagare and Bullough, 2020).

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.

New lighting technologies for vehicle lighting, including LEDs, laser sources, adaptive driving beam (ADB) systems, projection-based systems, and lighting elements for autonomous vehicles are proliferating globally. At the same time, our understanding of the impacts of these systems on vision, driving performance, comfort and perception is expanding rapidly. It is hoped that the references described in this report can provide a useful background on the performance, effectiveness, and—ultimately—safety potential of these evolving technologies.

11. INFORMATIVE 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

Brumbelow, M.L. (2015). A survey of horizontal road curvature for fatal nighttime crashes. *ISAL 2015 Proceedings*, 719.

- 32% of fatal crashes occurred along curves with radii less than 500 m.
- Run off the road fatal crashes resulted in collisions with a fixed object were common on small-radius curves.

Bullough, J.D. (2011). Safety benefits from daytime headlight use during inclement weather. *ISAL 2011 Proceedings*, 145-153.

- Based on data for fatal, multiple-vehicle, rainy-weather, crash data for states that enacted wipers-on, headlights-on legislation, there was an overall 7% reduction in fatal crashes associated with the use of headlights during rainy, daytime conditions.
- During rainy dusk or dawn conditions, the reduction in fatal, multiple-vehicle crashes was 30%.

Bullough, J.D., Donnell, E.T., and Rea, M.S. (2013). To illuminate or not to illuminate: Roadway lighting as it affects traffic safety at intersections. *Accident Analysis and Prevention*, 53(1), 65-77.

- Analytical estimations of visual performance improvements of roadway lighting in conjunction with vehicle headlighting were found to be strongly correlated with nighttime crash reductions at roadway intersections when improved lighting was present.

Gimbel, H.V., Van Westenbrugge J.A., Johnson W.H., Willerscheidt A.B., Sun, R., and Ferensowicz, M. (1993). Visual, refractive, and patient satisfaction results following bilateral photorefractive keratectomy for myopia (no. S5-S10). *Refractive and Corneal Surgery*, 9.

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

Green, E.R., Agent, K.R., Barrett, M.L. and Pigman, J.G. (2003). Roadway lighting and driver safety (no. KTC-03-12/SPR247-02-1F). *Kentucky Transportation Center*.

- 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 (no. AR-683). *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., and Flannagan M.J. (1990). Development of a headlight system performance evaluation tool (UMTRI-90-41). *University of Michigan*.

- An average adaptation luminance of 1 cd/m² while driving at night is derived.

Sullivan, J.M. and Flannagan, M.J. (2007). Determining the potential safety benefit of improved lighting in three pedestrian crash scenarios. *Accident Analysis and Prevention*, 39(3), 638-647.

- At speeds typically driven by people at night, better seeing than what is provided by low beam headlights is needed to help prevent crashes involving pedestrians.

Wilken, D., Ananthanarayanan, B., Hasson, P. Lutkevich, P.J., Watson, C.P., Burkett, K., Arens, J., Harward, J., and Unick, J. (2001). European road lighting technologies (no. FHWA-PL-01-034). *U.S. Department of Transportation*.

- 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.

NSC. (2002). Driving at night. *National Safety Council (NSC)*.

- Traffic death rates are three times greater at night than during the day; vision is limited at night compared to daytime; depth perception, color recognition, and peripheral vision are compromised after sundown.

Opiela, K., Andersen, C.K., and 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. and Flannagan, M.J. (1999). Assessing the potential benefit of adaptive headlighting using crash databases (no. UMTRI-99-21, HS-042 899). *University of Michigan*.

- 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.

Sullivan, J.M. and Flannagan, M.J. (2002). The role of ambient light level in fatal crashes: inferences from daylight saving time transitions. *Accident Analysis and Prevention*, 34(3), 487.

- Fewer pedestrian and animal crashes occurred during the light periods of the same clock time around the transitions to and from daylight savings time.
- Other crash types were relatively unaffected by the presence of light or dark.

11.2 Characteristics of Lighting and Impact on Vision

Forward lighting on vehicles serves several 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." To fully 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 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. and 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., and 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., and 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 15 degrees) improved with a “bluer” spectrum (metal halide) relative to a “yellower” one (high pressure sodium) as light level decreased below 1 cd/m².
- On-axis detection did not depend on spectrum at any light level.

Larkin, D. (2020). Impact of modern vehicle headlights on traffic signs. *3M*.

- An analysis of the photometric output of market-weighted beam patterns for halogen and LED headlights in North America (Flannagan, 2019) revealed that newer headlight systems produce up to 20% lower illumination levels on traffic signs than headlights from a decade earlier.

Lingard, R. and 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 degrees 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., and Hunter, C.M. (2002). Visual benefits of high-intensity discharge forward lighting (no. 2002-01-0259). *SAE International*.

- 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 and Flicker

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

- Oncoming low beam headlight glare degraded detection performance of a target 23 degrees off-axis but not 15 degrees off-axis.

Alferdinck, J.W.A.M. and Varkevisser, J. (1991). Discomfort glare from D1 headlamps of different size (no. IZF 1991 C-21). *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. and 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., and Bernstein, A. (1977). Modeling vision with headlights in a systems context (no. 770238). *SAE International*.

- 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 (no. S79). *Vision Research*, 35.

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

Bichão, I.C., Yager, D., and Meng, J. (1995). Disability glare: effects of temporal characteristic of the glare source and of the visual-field location of the test stimulus, *Journal of the Optical Society of America A* 12(10).

- A transient glare source raised threshold by 0.5 to 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. (2017). Developing a better understanding of discomfort glare: Cause and effect. *ISAL 2017 Proceedings*, 705.

- Discomfort glare is influenced by factors including the illuminance at the eyes, the angle between a glare source and the line of sight, the spectrum of the source, its size and maximum luminance, the background luminance, and the type of task the observer is doing when assessing the visual comfort.
- There are possible driving behavioral effects of discomfort glare including variability in speed or lane position.

Bullough, J.D., Van Derlofske, J., Fay, C.R., and Dee, (2003). Discomfort glare from headlamps: Interactions among spectrum, control of gaze, and background light level (no. 2003-01-0296). *SAE International*.

- A background light level ranging from 0.1 to 3 cd/m² 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., and Van Derlofske, J. (2002). Discomfort and disability glare from halogen and HID headlamp systems (no. 2002-01-0010). *SAE International*.

- 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. and Rea, M.S. (2001). Driving in snow: Effect of headlamp color at mesopic and photopic light levels. In *Lighting Technology Developments for Automobiles* (no. SP-1595). *SAE International*.

- 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., and Stevens, W.R. (1953). A note on the relative discomfort from mercury, sodium, and tungsten light sources. *GEC Journal*.

- 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., and 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., and Traube, E.C. (1993). Discomfort glare from high-intensity discharge headlamps: Effects of context and experience (no. UMTRI-93-10). *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 "glariness" is: red, yellow, green, blue.

Flannagan, M.J., Sivak, M., Gellatly, A.W., and Luoma, J. (1992). A field study of discomfort glare from high-intensity discharge headlamps (no. UMTRI-92-16). *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., and 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. and Hemion, R.H. (1968). Headlamp beam usage on U.S. highways (no. AR-666). *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., Toyofuku, Y., and Aoki, Y. (1999). Recovery time of visual acuity after exposure to a glare source. *Lighting Research and Technology*, 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 seconds 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.