Vehicle Forward Lighting: Optimizing for Visibility and Comfort

A Transportation Lighting Alliance Scoping Study

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Abstract
This report outlines a literature review performed by the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute to identify opportunities and to suggest priorities for further understanding of vehicle forward lighting and how it can be best optimized for visibility and comfort.

Keywords: automotive, headlamp, lamp, intensity, HID, halogen, color, comfort, glare, visibility, beam
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ABSTRACT
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INTRODUCTION

This report outlines a literature review performed by the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute to identify opportunities and to suggest priorities for further understanding of vehicle forward lighting and how it can be best optimized for visibility and comfort.

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.

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 and shape of the beam pattern
- location and mounting height of the light sources
- effects of dirt and water
- spectral power distribution or color
- system life and reliability

One of the objectives of the present report is to summarize existing information about these characteristics of lighting and to prioritize them in terms of their relative importance at meeting the objectives of lighting listed above, and the relative ease with which these aspects of lighting can be changed or modified. Such information will assist members of the Transportation Lighting Alliance in working together to optimize forward lighting systems.


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. A summary section at the end of the report provides recommendations for areas offering the greatest potential value for the design and optimization of forward lighting.
INTENSITY AND ILLUMINANCE

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 are 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.

Laboratory and Field Methods

The study of forward visibility using field methods is common and generally, have 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).
AIM AND SHAPE OF THE BEAM PATTERN

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.

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).
LOCATION AND MOUNTING HEIGHT

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.

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.
DIRT AND WATER

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

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.
SPECTRAL POWER DISTRIBUTION

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.

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).
SYSTEM LIFE AND RELIABILITY

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 of high intensity discharge 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.

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).
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. To this end, Table 1 lists each of the aspects of lighting discussed in previous sections of this report, their relative importance in providing visibility, comfort and appearance, and the relative ease with which these aspects can be studied or addressed in forward lighting configurations.

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Significance of aspect</th>
<th>Ease of addressing</th>
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<td>intensity/illuminance</td>
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<td>medium</td>
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<tr>
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<td>life/reliability</td>
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*Table 1. Relative Importance of Forward Lighting Aspects to Visibility, Comfort and Appearance*

The literature review provided in this report demonstrates that there are several important areas where gaps in knowledge exist and where future study would likely be fruitful:

- Long term effects of driver comfort. Few of the methods used to evaluate the characteristics of forward lighting move beyond short-term, immediate impacts of lighting systems. Lighting conditions that are uncomfortable might only result in degradation in performance after several hours of use or longer; most studies do not use extended periods of time.

- Improved understanding of peripheral vision. Studies of mesopic vision, for example, show that spectrum and other factors play important roles in visibility in the periphery. Most recommendations for lighting in the driving task address only on-axis vision.

- Interactions between forward lighting and ambient (fixed) roadway lighting. Recommendations for lighting typically address only one "mode" of lighting or visibility, but as described above, these are known to interact.

The literature reviewed in this report point to these areas as ones in which collaborative research activities can have the greatest impact.
ACKNOWLEDGMENTS

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**ANNOTATED REFERENCES**

**A. Importance of Lighting**

1. **Lighting, Visibility and Crashes**

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

   - 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

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

2. **Accident Statistics**

   - 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

   - 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) 40% 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

   - 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
B. Characteristics of Lighting and Impact on Vision

1. On-Axis and Off-Axis Vision

- 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

- 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

- 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

- off-axis detection (at 150) 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

- detection of peripheral objects from 120 to 290 off axis and with varying contrasts was improved with metal halide illumination relative to high pressure sodium illumination at mesopic light levels

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

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

- the spectral power distribution of fixed-pole lighting impacted peripheral detection more than one's own headlights

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

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

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

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

- 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

- 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
- 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

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

- 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

3. Light Output, Intensity and Illumination
- 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

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

- 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

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

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

  o 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

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

  o 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
  o the light distribution leads to shorter response times to peripheral targets

  o 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
  o 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
  o optimum lighting appears to be a town beam, based on dimming the present dipped headlight, giving a straight ahead intensity of 80 cd

4. Glare
  o 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
- 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

- 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

Akashi Y, Rea MS. 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

- 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

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

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

- 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

- 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

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

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

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

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

  o 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

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

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

   - 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

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

   - 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

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

   - 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

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

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

  o 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

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

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

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

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

  o 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
- 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

Olson, Paul L., Glare from following vehicles, SAE (Society of Automotive Engineers) Transactions, v 99, n Sect 6, 1990, 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.

5. Age Effects
- 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

- 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

- older drivers reported lower discomfort from oncoming headlights than younger drivers

Corwin A. Bennett, 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

- 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
Decarlo, Dawn K.; Scilley, Kay; Wells, Jennifer; Owsley, Cynthia, Driving habits and health-related quality of life in patients with age-related maculopathy, Optometry and Vision Science, v 80, n 3, Mar 1, 2003, 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

- a high percentage of older drivers' accidents occur in intersections when entering traffic or crossing a main road
- the problems may be in perception or attention, motor performance or inadequate interaction with other road users

C. Technical Aspects of Forward Lighting

1. Forward Lighting Task and Design Goals
- 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, foglamps, dipped beam patterns, and brake lamps

2. Headlamp Beam Patterns
- 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

3. Headlamp Mounting Height
Headlamp Mounting Height Task Force, 27 November 2000 Draft.
- near-foveal eyepoint illuminance levels of 3 to 4 lux for short duration were found
- for longer periods of time, the discomfort glare tolerance decreases to the range of 1.5 to 3 lux
- 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 lux
- a rapid increase in glare begins at about a 10cm height differential from reference
- maximum headlamp mounting height should include the 85th percentile driver.

4. Headlamp Leveling
- 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
Kare Rumar, Visibility distances in night driving with misaligned meeting dipped headlights, Department of Psychology, University of Uppsala, Sweden, Report 28, 1965
  o 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%

5. Headlamp Cleaning
  o headlamps on many vehicles were found to be misaimed and dirty, increasing glare illuminance to other drivers and reducing one’s own forward illuminance

Kare Rumar, Dirty Headlights – frequency and visibility effects, Department of Psychology, University of Uppsala, Sweden, Report 136, 1973
  o even in dry weather on seemingly clean roads, light reduction is normally 10-20%
  o in bad (slushy) road conditions few cars have light reduction below 50%
  o drivers normally do not react to light reduction below 60%
  o 60% light reduction causes a 20% reduction of high beam visibility and a 15% reduction of low beam visibility

6. AFS Headlamps
Adler, B., Lunenfeld,H., Evaluation of a three-beam vehicle lighting system, Transportation Research Record 502, pp.22-33, 1974
  o one new-term improvement for vehicle forward lighting is a 3-beam 4-head-lamp system: High beam, low beam and midbeam
  o a computer program calculated the glare in the rearview mirror as a following vehicle with different headlights system approached from the rear and evaluated the 4 modes achieved by combining the 3-phase beams
  o 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 $E=K(\text{candela output} \times \text{reflectivity})/(\text{oblique distance})^2$
  o 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
Josef Kalze, 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 model (VarioX-module), high beam, and static bending light and provides a comfortable compromise between visibility distance, reduced glare for oncoming traffic and comfortable spread of homogeneity
- 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

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

- The side area close to a car up to a distance 20-30m, called “No man’s land”, is considered to be illuminated by a new light function called static banding light
- Computer software—LDE was used to simulate and analysis the new light distribution

Stuart Birch, Adaptive front lighting, aei December 2001 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
  - 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 20 m in front of the vehicle—to keep reflection dazzle 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 curve
Takashi Sato and Shinichi Kojima, the smart headlamp system with variable low-beam pattern, SAE 2001-01-0845
- SHS (smart headlamp system) was evaluated in terms of visibility and discomfort glare. Discomfort glare evaluation used Schmit-Clausen’s and Bindels formula (de Boer scale).
- Visibility, isolux and glare were evaluated between SHS and conventional headlamp system.
- On coming glare of the SHS is slightly higher than conventional headlamp system but still within acceptable range.

Joseph S. Stam, Automatic vehicle high-beam headlamp control system, SAE 2001-01-0318
- An automatic switching of the high-beam headlamps system is introduced, with which vehicles provide a significant safety and less glare.

Michael Sivak, Michael Flannagan, Brandon Schoettle, Yoshhiro Nakata, Quantitative comparisons of the benefits of applying adaptive headlights to the current U.S and European–low beam patterns.
- The potential benefits of applying two embodiments of adaptive lighting to the U.S and European beam pattern: curve lighting that involves shifting the beam horizontally into the curve, and motorway lighting that involves shifting the beam vertically upward, were examined.
- Curve lighting would substantially improve seeing performance on curves for both types of beams. On right curve there would be an increase in disability glare for oncoming traffic. No major discomfort glare problems would be expected.
- Motorway lighting would substantially improve seeing performance.

Alexander von Hoffmann, Analysis of adaptive lighting distribution with AFSim
- Presents requirements for simulation software derived from measurements of the glare illuminance.
- Maximum swiveling angle: $a_{\text{MAX}} = \arcsin\left(\frac{100h}{2R}\right)$. $h$ is the headlamp height and $R$ is the radius of curve.
- Glare illuminance from oncoming AFS headlights with different cutoff angle was measured.
- One kind of simulation software AFSim is introduced.

Paul Sharke, Let light be there, 10 June 2001, Mechanical engineering
- This paper reviewed the AFS technology and introduced the EURKEA study.
- Lighting that reduced glare on wet roads helped both the driver and oncoming drivers.
- The more intense a glare, the more it disturbed oncoming drivers.
- The size of the light source affected the level of discomfort. After sources were normalized to the same luminous intensity, the small areas of glare are more disturbing than large ones.
- Light pulses lasting longer than 8 to 10 seconds degraded visual performance because of the longer time for eyes to readapt to lower light levels one the pulse ceased.
- NHTSA reported complaints about glare from identify HID headlamps and sport utility vehicle headlamps, claiming that both are too bright and the latter are too high.

Preeti Bajaj, Shubhalaxmi Kher, Smart control of headlight intensity of automobiles for improved night vision, SICE’99 July 28-20, Morioka
- This paper proposed design of a controller to provide optimal illumination at all distances when the vehicles are in vicinity. It uses a fuzzy logic method to decide proper headlight intensity based on driving speed, distance from other vehicles, driving action, weather condition and road geometry.
Michael Hamm, Ernst-olaf Rosenhahn, System strategies and technology for improved safety and comfort with adaptive headlamps
- Glare effects during road driving for different headlamp algorithms are carried out. These investigations show that adaptive curve lights can reduce glare by using suitable curve light parameters
- Predicting curve light system and steering wheel controlled light systems are better than conventional systems in regarding glare

- 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°C. Furthermore, the fog lamp system allows control of the beam pattern side irradiation in a range of 30° to 50° toward the road shoulder. The results of prototype testing of this forward lighting system are presented

- 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

Miura, Jun(Osaka Univ); Ito, Motokuni; Shirai, Yoshiaki, Three-level control architecture for autonomous vehicle driving in a dynamic and uncertain traffic environment, IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC, 1997, 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.

7. Lighting on Trucks and Buses
Helder, Dorothy J., Large-area variable reflectance mirrors for trucks and buses, SAE Technical Paper Series, 912705, 1991, 6p
- Variable reflectance mirrors, such as those utilizing electrochromic and liquid crystal technology, are capable of multiple reflectance levels; with variable reflectance, the driver can select a high reflectivity level during daytime driving or when reversing into loading docks, and can select a reduced dimmer reflectance level when driving during glaring conditions
8. Lighting on Motorcycles

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- using comprehensive police crash data, the differences between impaired and nonimpaired riders involved in crashes, in terms of various demographic characteristics, helmet use, license status, roadway environments, and injury outcomes, are described
- in addition to age-specific determinants of impaired crash involvement, time factors such as weekends and night-time, and licensing (out-of-state or no licenses) are strongly associated with impaired rider crashes

D. Light Source Technology

1. Halogen Source Characteristics

- the design life of the entire halogen forward lighting series for automotive applications is redesigned
- effects of the known design parameters and how they affect halogen lamp life are discussed along with supporting design choices
- the contribution/cost tradeoffs are examined in order to explain the final product configuration.

Engelhard, Klaus, Low voltage tungsten halogen lamps, Electrical World (Melbourne, Australia), v 61, n 1, Jan, 1996, p 18
- low-voltage tungsten halogen lamps have now a place in automotive and signalling systems as well as in general indoor and outdoor lighting
- lamp life, luminous flux, a luminaire efficiency are influenced by external factors to a much greater degree than standard incandescent lamps

2. Xenon Gas Discharge Light Sources (HID)

- multichip ICs can be used to produce compact, lightweight, low-cost electronic ballasts for automotive HID headlamps

Jost, Kevin, Anatomy of high-intensity discharge headlamps, Automotive Engineering (Warrendale, Pennsylvania), v 103, n 11, Nov, 1995, p 38-42
- for automotive high-intensity discharge lighting, modifications were made to address component size and lighting performance parameters, and governmental standards for forward lighting had to be altered before the systems could be introduced
- compared to conventional halogen headlamps, discharge systems provide higher performance and efficiency, improved durability, white light, and more consistent output regardless of voltage supplied by the vehicle
Lee, Kyu-Chan(Seoul Natl Univ); Cho, Bo H., Design and analysis of automotive HID lamp ballast system using auxiliary winding, PESC Record - IEEE Annual Power Electronics Specialists Conference, v 1, 2000, p 544-549
- a new scheme for automotive high intensity discharge (HID) lamp ballast systems is proposed
- the proposed scheme separates the input voltage of the ignitor from the dc link voltage using auxiliary winding, which results in the use of the lower voltage rating power devices for the HID lamp ballast system, compared with the conventional system
- as a result, the proposed system has a lower cost and higher efficiency

3. LED Light Source Characteristics
- due to their reliability, small size, lower power consumption, and lower heat generation, LEDs are a natural source choice for automotive lighting systems
- with the advent of new higher packages, and with the promise of even higher light output in the near future, the use of white LEDs sources for all vehicle forward lighting applications is beginning to be considered

4. Distributive Lighting, Fiber Optics and Light Guides
Van Derlofske, John F. (Lighting Research Center, Rensselaer Polytechnic Institute), Low beam head lamp design using distributive lighting system, Proceedings of SPIE - The International Society for Optical Engineering, v 4445, 2001, p 119-129
- due to their small size, lower power consumption, and lower heat generation, LEDs are a natural source choice for display illumination
- the conversion of an LED's output flux distribution to one that is uniform over a given area can be accomplished with plastic, injection-molded light pipes

Hoines, Lilian(North American Lighting, Inc); Potter, Brant; Lekson, Matthew; Strauss, Benjamin, Design considerations in exterior automotive courtesy lighting, SAE Special Publications, v 1323, Feb, 1998, 980009, Automotive Lighting Technology, p 45-49
- use of LEDs, light guides, and electroluminescence can result in pleasing styling along with the ability to outperform conventional sources

E. Roadway Lighting Systems

1. System Interaction and Optimization
- in order to evaluate the visibility of real roadway objects it is necessary to include the effect of both the vehicle head lighting system and the fixed lighting system
- light coming towards the observer from a fixed lighting luminaire does not improve the visibility of large or complex objects seen against a background other than pavement or which are recognized by internal contrasts

- the spectral power distribution of fixed-pole lighting impacted peripheral detection more than one's own headlights
Lewin, Ian, Lamp spectral effects at roadway lighting levels Source: Lighting Journal, v 64, n 2, 1999, 6 pp
- research has been conducted to determine whether the spectral distribution of a light source has any effect on the visibility it produces
- it was found that lamp spectral distribution influences human perception in several different ways at low light levels

**F. Regional Differences**

**1. U.S. Beam Patterns in Comparison to European and Japanese Patterns**

Sivak, Michael; Flannagan, Michael; Chandra, Divya; Gellatly, Andrew, Visual aiming of European and U.S. low-beam headlamps, SAE Technical Paper Series, 920814, 1992, p 1-10
- the location of the perceived cutoff of a headlamp beam was generally near the location of the maximum contrast between adjacent vertical parts of the beam pattern
- the variability of the aiming performance was systematically related to the magnitude of the maximum contrast

- aiming of dipped-beam headlamp is currently performed visually in Europe, using the cut-off line in the beam pattern
- a good definition of a visual cut-off would allow uniformity in interpretations