Developments since the 2008 NHTSA Report to Congress on Headlight Glare

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The 2008 NHTSA report [1] identifies and describes some major factors of glare as the most likely reasons behind the growing number of complaints at the time. Since then, these properties of automotive lights have moved further in the unfavorable direction, while technological progress has also introduced novel challenges. In this letter, I will focus on what has changed in the past years and offer some further points for consideration.

1 Luminance

Natural scenes – whether under sunlight or at night – consist of visual elements of low contrast, which means that the luminance levels of different parts of the visual field are not too different from each other. Electric light sources at night cause unnaturally high contrast, an evolutionarily novel challenge which our visual system cannot solve. This leads to discomfort and the inability to resolve details of the scene – in other words, it leads to various forms of glare. A core reason behind problematic levels of contrast in night-time traffic is therefore the luminance (perceived as brightness) of electric light sources.

Through the past two decades, the luminance of automotive lamps has increased for three main reasons:

1.1 Luminous flux and luminance

The NHTSA report mentions the increased output (flux) of then novel HID light sources. This technology has since been overtaken by solid-state lighting (LEDs and lasers) that offer even higher efficiency. The resulting increase in luminous output is used for greater illumination of the road and better visibility for the driver. At a fixed size of the light source, however, this increase also leads to an increase in luminance (more light has to come out of the same surface).

Even if luminous surfaces would scale with the increase in luminous flux of automotive headlights, glare to other road users would still increase because glare is also a factor of illumination at the eye [2] (the total quantity of light from the source that eventually reaches the viewer) and not only of luminance. This is the trade-off that is discussed by the NHTSA report and its summary: “Light levels are a compromise. A glare source to one driver is a source of seeing light to another driver.”

1.2 Size of the light source and luminance

New technologies, however, have also allowed for a decrease in luminous surface size. Due to reasons of design, packaging, and beam control, the use of this opportunity has further increased luminance in all types of automotive lamps (since a given quantity of light has to leave from a smaller area). When it comes to glare from lower beam, smaller luminous surface has an additional disadvantage: water droplets or dirt on the cover lens cause a more severe distortion of the beam pattern relative to the effect of the same stain on the beam when it is emitted from a larger surface.

1.3 Light intensity distribution

The so-called "directionality" of LEDs and lasers derives from their light emitting surfaces being flat (as opposed to curved surfaces in other technologies). This results in a peak in intensity along the center-line of the produced beam [3], while other light sources produce an even distribution (equal intensity in all directions). Optical means (reflectors and lenses) to shape the beam in current automotive headlamps do not fundamentally alter this property. Unfortunately, I am not aware of any studies directly assessing the effects of this difference between prior and solid state sources on perceived brightness and glare. There are two reasons why it appears feasible, however, that perception is negatively affected by the change in light source technology:

1. Visual acuity
   The spatial resolution of the human eye is high enough to discriminate between the luminance of various parts of a light source, taking the average size of an automotive lamp as viewed from less than $\sim$ 150 ft (relevant mainly in urban traffic) and possibly also at larger distances [4]. Therefore, measuring the average luminance may not be fully informative, and such a metric cannot differentiate between e.g. a halogen and an LED source in this regard. Luminance measurements to determine glare should therefore be detailed at a sufficiently high resolution, and maximum luminance values should be taken into consideration instead of the average across a larger surface.

2. Perception of a Gaussian distribution
   Several experiments have shown that we have an innate aversion to Gaussian light intensity distributions. Visual elements involving such a feature appear as brighter [5] ("glare illusion"), possibly due to their resemblance to the sun [6]. To my knowledge, this mechanism has not yet been dissected experimentally regarding the currently used lighting technologies, but it is feasible to think that light intensity distributions that trigger the above avoidance mechanism would appear as more glaring.

To solve these issues, novel optical solutions could be utilized to provide a homogeneous intensity distribution (see 5.1).

2 Color

The relationship between luminance and the perception of brightness is affected by several factors, including the spectral power distribution of light.

2.1 Cool vs. warm light

A high relative contribution of the blue portion of the visible spectrum leads to "colder" (bluer) apparent color, the physiological assumption of day-time (circadian stimulation), and a general assertion of potential danger (sunlight only contains large proportions of blue when the sun is high – which is linked to photo-toxicity by blue light and possibility of harm by ultra-violet light and heat). For these reasons, blue light has an invigorating effect and it also leads to an increased likelihood of discomfort glare and avoidance behavior. Indeed, the literature is clear on bluer light sources causing higher levels of discomfort glare in automotive settings [7, 8].

Current regulatory limits on color temperature are treated as the target to reach: since measurement and enforcement of these limits is problematic, they are also often exceeded with no repercussion [9, 10]. Furthermore, as LEDs age, the phosphor material that converts part of their primary (blue) output to lower frequencies deteriorates, leading to a continued shift towards colder color temperatures.

2.2 Saturation

More saturated colors are perceived as brighter [11] and thus have a higher propensity to cause glare. Due to their spectral characteristics, LEDs can produce higher color saturation than the filtering of true full-spectrum light sources (i.e. halogen or incandescent light bulbs). While this effect is not a major concern on its own, it might contribute to some extent to complaints of glare, for example by tail or indicator lights.

2.3 Color separation

As detailed in the NHTSA report, reflectors in older vehicle lamps are replaced by projector optics in newer ones. This trend has continued in the past decade as well, contributing not only to the smaller size of modern headlamps but also causing different parts of the emitted spectrum to project to different parts of the beam pattern. Unique to this technology, the spatial shift of different wavelengths causes a rainbow effect, most noticeably at the top edge of a lower beam pattern [9]. Since this is the region of the beam that oncoming traffic is most likely to encounter (under circumstances such as a bump in the road, elevation difference, etc.), the temporary shift in appearance towards colder color temperature can draw unnecessary attention and contribute to glare.

3 Flicker

A flickering light source produces higher luminance at certain times and lower luminance at others (it goes on and off). Depending on the frequency of this change (and other factors such as size, contrast, eye movements of the viewer, and more), a flickering light can appear continuous to us. Unfortunately, it has not yet been studied whether flicker contributes to glare in traffic or if measuring the average luminance across time is a sufficient metric to use for predicting glare (as is currently assumed for automotive lamps). Nevertheless, it is clear that flickering sources appear slightly brighter [12].

We have much more detailed knowledge of how flicker affects other aspects of perception [13]. Since some of these effects are subjectively similar to the discomfort caused by glare, they might be lumped together with what we assume to be the effects of glare when analyzing reports of distressed road users or experimental data on discomfort glare.

Flicker should be avoided at all times in all lighting applications – however, it is exceedingly present in traffic scenarios. The greatest contributor on modern streets are LEDs, where dimming is commonly achieved by pulse width modulation (rapid switching on and off of the source). When observing the tail lights or day-time running lights (DRLs) of many modern cars, this rapid flickering can be identified by the appearance of an array of repetitions of the same light image (a phantom array) during eye movements [14], or a buoyant appearance of the source. Since eye movements are particularly frequent and rapid during driving, this effect is not only distracting and a contributor to fatigue, but it can also cause spatial mislocalization of the light source [15]. Earlier vehicle lights did not produce high-frequency flicker.

4 Some other factors

4.1 Demographics and worsening eye health

Some other aspects of traffic have also changed unfavorably since 2008. The aging eye allows less light to pass through to the retina – particularly in the blue portion of the spectrum due to a yellowing of transparent structures. While this might decrease discomfort glare, it certainly increases disability glare due to scattered light in the eye. Elderly can nevertheless also be susceptible to discomfort glare and the problems discussed in this letter have generally more severe consequences to those with worse vision [16], particularly when it comes to traffic safety.

4.2 Mount height

The issue of headlamp height is described in the 2008 NHTSA report. Since then, the size of most vehicles and the popularity of SUVs have grown, making this question more relevant. Excessive glare might be one factor behind this trend, since sitting higher offers some reduction in glare from other vehicles – potentially creating a positive feedback loop of questionable sustainability.

4.3 Lamp layout

LEDs have also allowed designers to experiment with novel configurations. The first trend was displaying bare LED chips (with no diffuser on top) for both DRLs and tail lamps. More recently, this has changed into thin stripes of diffusers and light guides.

Glare is more pronounced from non-uniform sources [17]. Thus, both of the above solutions have potential to increase glare, from distances where the spatial frequency of the generated patterns are discernible and relevant to pattern glare [18]. Conversely, using the possibility of shaping lamps in ways which were not possible or feasible with preceding sources, object perception could be aided [19]. Together with the use of warmer colors, larger surfaces in configurations that lead to a more homogeneous appearance could be used to decrease glare.

4.4 Digital displays

The use of lighting and display devices in car interiors holds potential for distraction and worse visual performance in traffic. Current displays are primarily back-lit with LED sources that have a primary output exactly in the frequency range (see 2.1) with highest potential to disrupt dark adaptation. When the driver's gaze alternates between a display device and the road at night, a natural consequence might be a need for higher levels (and potentially colder color) of road illumination to compensate for the worsened dark, accommodative, and color adaptation to the outside scene.

Display use in vehicles was not yet so prevalent in 2008. While the average display size and frequency of use is possibly still increasing, many manufacturers have reacted to the problem by providing a dark mode for the user interface. More expensive models have just recently started to use OLED technology, where dark modes can be better implemented – although non-black parts of the screen are still dominated by blue, and OLED technology can only offer minor mitigation against the above issue.

4.5 Erroneous assumptions behind guidance and regulation

The blink reflex is assumed to protect us from looking at an overly bright light source. The error in this line of thinking has been pointed out experimentally [20] as well as anecdotally through people who have damaged their retinas by staring at the high sun [21].

When it comes to traffic, this assumption is further extended by the common advice to avoid looking at vehicle headlights. Following this piece of advice is often not possible, because (i) eye movements tend to be unconscious [22]; (ii) initial gaze response is largely driven by low-level salience [23] – therefore, a brighter light source will more likely lead us to rapidly look at it, even if it is glaring; (iii) indicator lamps are placed just adjacent to the main glare sources on vehicles, forcing road users to gaze at the lamps of all relevant vehicles at an intersection or other traffic situation.

5 Solutions

The trade-off between driver visibility and glare to other road users, as stated by the NHTSA report, is a constant dilemma. This is discussed under 1.1 of the present letter. Note, however, that all other points mentioned above are *not* part of this trade-off, offering ways to decrease glare while maintaining the contemporary standard of higher road illumination levels.

5.1 Beam shaping and luminous surface

Luminance can be decreased by increasing surface size. Technologically, indicator lamps, tail lamps, and DRLs can achieve this goal by use of light guides.

Where beam pattern is strictly defined (lower and upper beam), the solution is less straight-forward. The perceptual difficulties originating from the unusual light intensity distribution of LED sources have been noticed by many engineers. Various solutions using light guides, lens arrays, and diffusers have been proposed [24, 25], and it seems technically feasible to both alter the unfavorable light intensity distribution as well as increase surface size (while retaining beam control).

5.2 Luminous surrounds and color

Even without any modification of current headlight optics, established technologies can be used to mitigate glare from headlights. Light sources of warmer output could be utilized: this change alone would already lead to a significant reduction in glare.

A small glare source also appears less unpleasant when it is surrounded by a larger luminous surface, particularly when that is of warm color [26]. DRL configurations could be applied along these lines, with increased surface size and decreased luminance and color temperature.

5.3 Employing object perception

Such luminous surfaces could also be used to emphasize object characteristics of the vehicle. By doing so, they would facilitate higher level visual processes leading to better perceptual efficiency and thus to less fatigue.

While direct studies of similar solutions are so far scarce [19], our basic understanding of object-based attentional processes and eye movements [27] as well as some early empirical work [19, 28] indicate that corresponding implementations would have benefits on several levels. Point-like light sources do not provide perceptual cues of vehicle size, identity, or often even orientation and distance. Providing these cues with shapes that more closely resemble the vehicle's appearance in day-time would lead to perceptual advantages not only regarding the vehicle in question but also in awareness of the traffic scenario as a whole. Naturally, extending the size of luminous surfaces holds potential for overlighting, if luminance (and color temperature) is not capped appropriately.

5.4 Adaptive technologies

Adaptive driving beam (ADB) systems aim to illuminate important parts of the visual scene for the driver while reducing illumination towards other vehicles. In order to do this, the system has to detect and identify components of the scene and utilize a sufficiently high level of beam control to direct light independently at these elements.

5.4.1 The goal of ADB

ADB systems aim to "improve long-range visibility for the driver without causing discomfort, distraction, or glare to other road users" [29]. Therefore, they offer a flexible intermediate solution between upper and lower beam.

The primary goal of this pursuit is not to reduce glare to oncoming traffic below the regulated limits of lower beam, but rather to increase road illumination relative to lower beam without exceeding the existing regulatory limits. This is frequently formulated as a reduction of glare, commonly causing misunderstanding. Here, reduction is relative to high beam – while the goal is to offer driver visibility on par with that of the high beam.

5.4.2 Limitations

ADB changes with every model generation. The most extensive study to date was done by the NHTSA in 2015 [29], on what was then state of the art on the European market. In many traffic situations, the tested systems produced higher levels of glare than lower beam levels, exceeding legal limits. Results also showed that smaller vehicles were less likely to be detected (and cut out from the beam pattern).

This is in line with the common experience in Europe, where older vehicles (with halogen headlights) and two-wheelers or other vulnerable road users are often missed by ADB. On the other hand, several systems explicitly highlight detected pedestrians with the adaptive beam. While this is based on the assumption that their chances of being missed by the driver will be lower, it undoubtedly increases the glare experienced by them. It can also decrease their visibility from the viewpoint of other road users, particularly from the opposite direction.

The 2015 NHTSA report has also found several instances where ADB systems acted in illegal ways. Some of the actions are erroneous and can be expected to take place less frequently as the systems evolve. These mistakes include turning the upper beam on in urban areas or at low speed, leaving the upper beam on even when there is no input regarding the road situation (occluded sensors), or abruptly darkening the forward roadway due to erroneous object identification.

A further limitation is that ADB response delay to suddenly appearing vehicles causes the upper beam to dazzle oncoming drivers for a brief (0.5-1.92 s) time [29]. Unfortunately, while this duration might decrease as the systems improve, ADB will likely not be on par with human performance due to the different mechanism behind how it works. Humans anticipate the appearance of another vehicle from the movement of its headlights (e.g. at a curve), but ADB needs to wait until the two headlamps are both visible to its sensors to even begin the process of identifying and masking the area of the oncoming vehicle. Similarly, the headlights of a truck on the opposing lane of a divided roadway are often not visible due to the median barrier. In this situation, a human driver is required to switch to lower beam in order to avoid dazzling the truck driver (who has unoccluded line of sight due to an elevated seating position). ADB systems, however, only look for the headlight pattern and do not take action in this case. A legal dilemma in Europe is that while a human would fail the driving test for behaviors such as the examples above, currently accepted ADB systems produce these errors reliably.

5.4.3 Effects on high-level perception

As the 2015 NHTSA report points out, "ADB engagement may be a source of distraction for the driver of the ADB-equipped vehicle because of the visually discernible changing beam pattern."

ADB may not only distract the driver, but also deprive other road users from reliable visual cues regarding the motion of the vehicle with ADB. On the one hand, our situation awareness have so far relied on the congruency between the movements of a car and those of its headlight beam, and this coupling is now sometimes present, sometimes not. On the other hand, change elicits attentional orienting – and ADB to other road users appears as constantly changing and flashing lights. While these effects most likely increase perceptual load, such phenomena have not yet been studied experimentally.

ADB systems are advertised as "glare-free," which is demonstrably misleading. Research in the field is scarce and the vast majority of it is closely tied to the industry. There is also a common misunderstanding of what is meant by glare reduction (5.4.1). While the ever improving implementations allow for directed glare reduction, the primary aim is to increase illumination while keeping glare within the existing legal limits of lower beam, thereby reducing glare relative to illumination level, or as compared to traditional upper beam. Adaptive technologies hold much potential, but waiting for their final form as the silver bullet to solve all glare problems would likely lead us to miss out on solutions that are already accessible.

5.5 Filtering

The wide-spread use of various forms of filtering (glasses or visors) indicates that many have difficulties with glare at night. Color filtering against glare works by reducing exposure to blue light while allowing the rest of the spectrum through. Polar filters aim to reduce glare from reflections on the road. Since glare from mirrors is also a frequently noted issue, more expensive cars increasingly offer auto-dimming side mirrors as well (on top of the traditional filtering mode of rear-view mirrors).

While these solutions can effectively reduce glare, they always reduce visibility of darker elements of the visual scene (for example, an unlit pedestrian will become less discernible against a dark background). Thereby they highlight the essence of the issue, which is our perceptual inability to deal with high contrast: as newer vehicles emit more light, all other participants in traffic become relatively less visible.

6 Conclusion

Given the rapid progress of lighting technology in the past decade, a more contemporary revision of the situation seems advisable. Our current understanding of human perception together with novel possibilities in lighting design suggest an abundance of possibilities for glare-reduction without diminishing road illumination.

From the regulatory perspective, (i) setting a reasonable upper limit of luminance for all lamps, (ii) lowering the current upper limit of correlated color temperature for white light sources, and (iii) controlling for flicker would certainly decrease glare and would likely drive innovation and cultural trends in a more favorable direction. With lower maximally allowed luminance, luminous surfaces would increase in size, potentially also requiring total luminous flux to be capped in order to avoid overlighting.

The resulting change would inevitably lead to a decrease of contrast – the issue that our visual system cannot solve. This new generation of automotive lamps could also be designed in shapes which aid object perception and reduce attentional load.

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