Why is Headlight Glare Such a Persistent Problem for the Driving Public? A Review

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ABSTRACT

From the perspective of the U.S. motoring public, headlight glare is one of the most persistent and widely recognized issues faced by drivers. Automotive forward lighting technologies have evolved dramatically within the past three decades from a single technology (filament sources) with only a few fixed, standardized form factors (round and rectangular sealed beam lamps) to a bewildering array of shapes, configurations and functionalities, using light-emitting diode (LED) and other solid-state sources. Most if not all LED headlights have a white or bluish-white appearance, which appear brighter and even more uncomfortable to oncoming and preceding drivers. Vehicles in the U.S. driving fleet have also grown larger and taller, and the distributions of headlight beam patterns appear to have undergone some modest changes as well. Finally, many headlights are not properly aimed although there is some evidence that the aim of headlights on brand new vehicles may have improved in recent years. All of these facts contribute to the sensation of headlight glare while driving at night. The present paper describes how headlight glare is defined and the implications of various countermeasures for glare from vehicle headlights.

Key words: Discomfort Glare, Disability Glare, Mounting Height, Headlight Aim, Adaptive Headlights

INTRODUCTION

For as long as there have been automotive headlights, there has been headlight glare (*1*). For most of the 20th century, vehicle forward lighting supporting driver visibility at night used filament sources. These lamps produce a yellowish-white, "warm" color of illumination with a correlated color temperature (CCT) of 2700-3000 K (*2*). Until the 1980s, sealed-beam incandescent sources in one of a few circular or rectangular shapes were universally deployed on all passenger and commercial vehicles in the U.S. Beginning in the mid-1980s, replaceable halogen bulbs began to be permitted for vehicle headlighting, permitting a wider range of styling and optical designs using reflectors, lenses and projectors to create headlamp beam patterns meeting the Federal Motor Vehicle Safety Standard (FMVSS) No. 108 (*3*). According to FMVSS 108, vehicle headlights must contain both high and low beam functionalities. High beams are meant to be used when no oncoming or preceding vehicles are present, providing a relatively large quantity of light both below and above the horizon line. Because they produce a substantial amount of light above the horizon, high beam headlights can be very glaring to other drivers.

Low beam headlights are meant for use when opposing and preceding vehicles are present and are generally the "default" headlighting system used by most drivers especially in urban locations, but also in rural locations even when no other vehicles are present (*4*). FMVSS 108 standards for low-beam headlights include angular locations where there is either a minimum required luminous intensity (to ensure sufficient visibility), a maximum permitted intensity (to prevent excessive glare), or both. **Table 1** shows selected low beam photometric requirements from FMVSS 108 (*3*), and **Figure 1** shows the distribution of photometric test locations (*3,5*), defined in terms of vertical and horizontal angles relative to the forward axis of the headlight. (Also shown in **Figure 1** is a schematic of a two-lane road indicating the approximate location of each test location in the driving environment.) As a consequence of these requirements, low beam headlights produce a broad, horizontal swath of light and exhibit a gradient near the horizon (*5*), above which intensities are low to avoid glare to other drivers (**Figure 2**).

TABLE 1 Selected Luminous Intensity Requirements for Low Beam Headlights (*3*)

Angular location (degrees)	Maximum luminous intensity (cd)	Minimum luminous intensity (cd)
8° left, 0° up and 8° right, 0° up	—	64
8° left, 4° up and 8° right, 4° up	—	64
4° left, 0° up and 4° right, 0° up	—	125
4° left, 2° up and 4° right, 2° up	—	125
1.5° right, 0.5° down	20,000	8,000
6° left, 1° down	—	750
2° right, 1.5° down	—	15,000
9° left, 1.5° down and 9° right, 1.5° down	—	750
15° left, 2° down and 15° right, 2° down	—	700
1.5° left, 1° up	700	—
1.5° left, 0.5° up	1,000	—
1.5° left, 0.5° down	3,000	—
1° right, 1.5° up	1,400	—
1° right, 0.5° up, 2° right, 0.5° up, and 3° right, 0.5° up	2,700	—
4° right, 4° down	8,000	—

Because filament sources (incandescent and halogen lamps) have relatively low efficacy (*2*), producing 10-15 lumens per watt (lm/W), low beam headlights using these sources are typically limited to about 55 W to avoid an excessive draw on the vehicle's electrical system. Producing a beam pattern meeting FMVSS 108 requirements, producing the minimum intensities where required while not exceeding the maximum intensities, is an optical engineering challenge, and with filament sources there is generally little "extra" luminous flux to distribute once the minimum requirements are met.

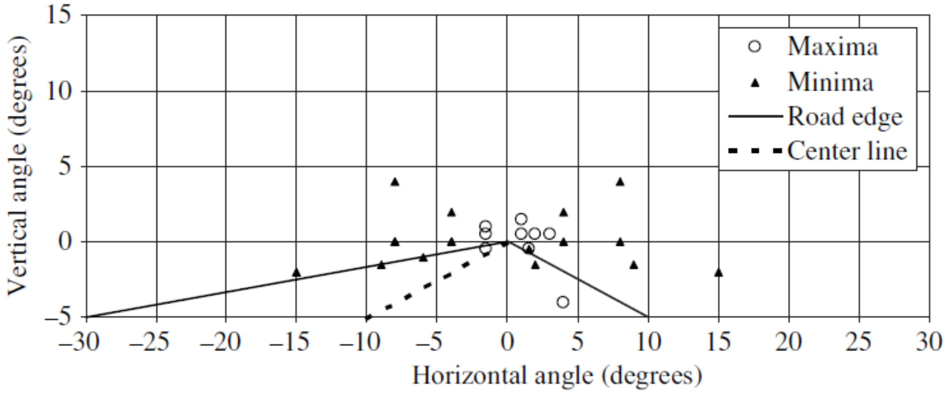

Figure 1 Angular locations of low beam photometric test locations superimposed on a road scene (*3*,*5*)

Figure 2 Photograph of a low beam headlight pattern projected onto a vertical surface (*5*); the horizontal cutoff on the right side of the image corresponds to a vertical angle of 0°

In the mid-1990s, some vehicles began to use high-intensity discharge (HID) lamps, similar in construction to metal halide lamps used at that time for sports and outdoor lighting. HID lamps are more efficient (50-60 lm/W) and have longer operating lives than filament lamps (*2*). They also tend to produce a "whiter" or "bluer" color of illumination (with a CCT of 4000-5000 K) that makes the roadway appear brighter [brightness is a subjective sensation of the amount of light emitted by a light source or reflected from a lighted object (*2*)] even when matched in terms of photometric quantities (*6*). In the 2000s, light-emitting diode (LED) sources began to be used for automobile headlights. These sources are even more durable than HID lamps, and more efficient (100+ lm/W), producing the same amount of light as a halogen headlight with only a fraction of the power, resulting in significant energy savings and emissions reductions (*7*). Whereas less than 10 years ago, vehicles contained a mixture of halogen, HID and LED headlights, at present almost all new vehicles manufactured contain LED headlights (**Figure 3**).

LED headlights typically produce an even "bluer" illumination color than many HID sources, with a CCT of 6000 K being very common (*8*). Not only is this color difference very noticeable, but it can also have implications for the perception of glare, and the "bluer" color of LED headlights is often cited as a factor in complaints about glare from LED automotive lighting (*9*).

DEFINITIONS OF GLARE

When driving at night, a driver needs to be able to see objects located hundreds of feet in front of a vehicle, in order to respond by steering or stopping to avoid a collision. Consequently, headlights are intense, and because they are used at night when the ambient environment is dark, the resulting contrast between headlights and the rest of the roadway scene provides a serious challenge to many nighttime drivers (*9*). Glare reduces visibility (disability glare) and makes drivers uncomfortable (discomfort glare).

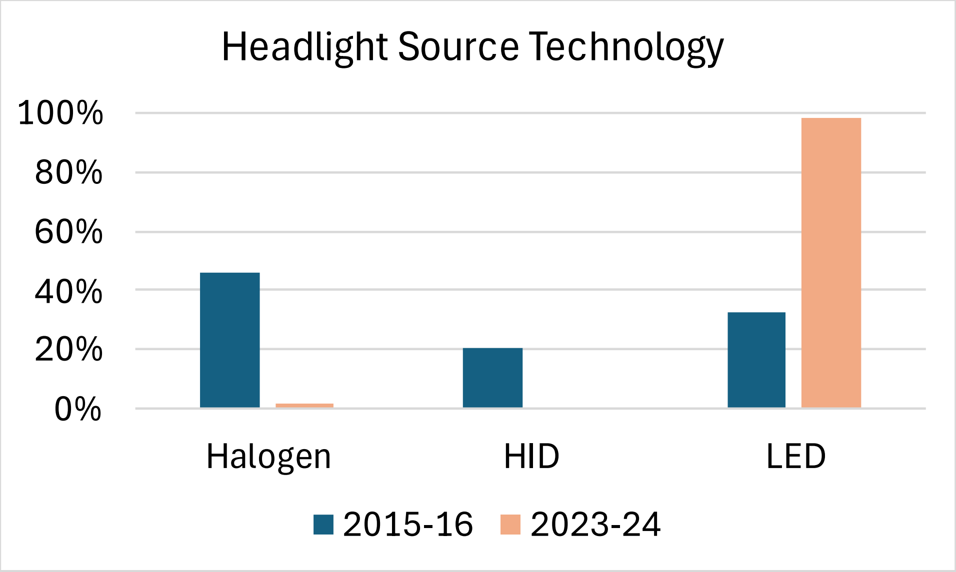

Figure 3 Prevalence of halogen, HID and LED headlamps in different years (Source: techdata.iihs.org)

Disability Glare

Because the media within the eye are not perfectly transparent, any light entering the eye will create some scattered light within the eye that acts like a luminous "veil" reducing the apparent contrast within the field of view (*10*). This effect is most prominent when the ambient light level is lowest (such as during the nighttime) and affects the visibility of low-contrast objects most. It is unfortunate that pedestrians commonly wear dark clothing resulting in low contrast between themselves and their backgrounds at night (*11*). The effect of scattered light is also largest when the glare source is close to one's line of sight; the magnitude of the luminous veil produced by a glare source is inversely proportional to the square of the angle between the source and the line of sight (*10*). In addition, the color of glare illumination does not affect disability glare (*12*), only the photometric intensity of light reaching the eyes. Despite the clear safety implications of glare on visibility and hence safety at night, drivers are not consistently aware of disability glare. Even dashboard lights, if they are adjusted to their maximum brightness level, can serve as a source of disability glare, but many drivers do not notice their impaired visibility (*9*).

Discomfort Glare

When drivers complain about glare from headlights, they usually refer to the annoying or even painful sensations that they experience when a bright light such as a vehicle headlight is shining into their eyes. This sensation of annoyance or even pain is defined as discomfort glare (*2*). While oncoming headlights at night can be a source of both discomfort and disability glare, these two forms of glare are not always simultaneous. The previously-mentioned dashboard lights that can produce substantial disability glare are unlikely to create a sensation of discomfort in most individuals (*9*).

FACTORS CONTRIBUTING TO HEADLIGHT GLARE

Intensity

Oncoming high beams are more glaring to drivers because they have a higher intensity than low-beam headlights (*3*), and this is why drivers must "dip" their headlights in the presence of oncoming or preceding drivers. Yet, despite the FMVSS 108 standards for automotive headlights remaining largely the same for several decades, complaints about headlight glare from low beam headlights seem to have been increasing, not remaining steady, in recent years (*13*). It does not seem, however, that the use of high-efficacy LED sources has increased the amount of light produced by headlights relative to halogen headlights. **Figure 4** shows market-weighted intensities for a range of vertical angles (above and below the horizon) produced in the forward direction by headlamps on 2004 model year vehicles (*14*) when halogen lamps were almost exclusively used on vehicles, and on 2019 model year vehicles (*15*) for both halogen and LED headlights. For positive vertical angles (above the horizon) there is relatively little intensity, but the intensity increases rapidly for the negative vertical angles (below the horizon) that result in useful illumination along the road.

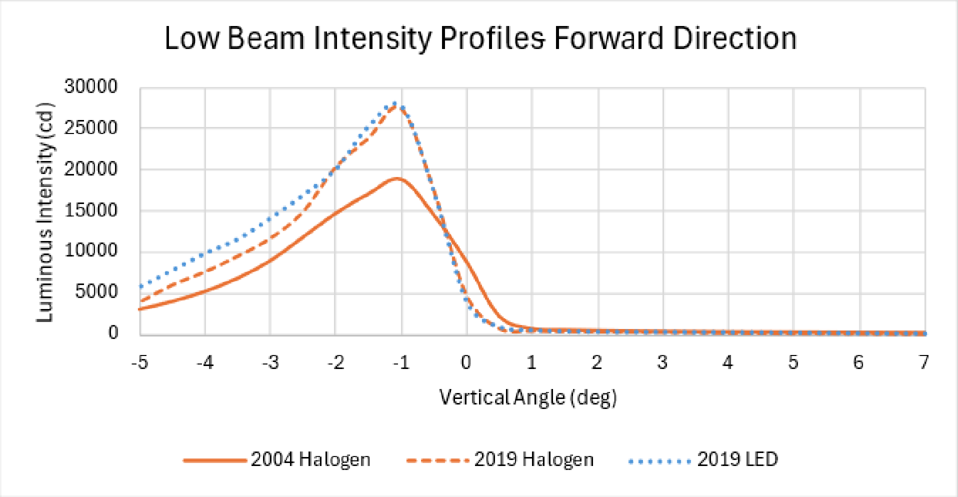

Figure 4 Intensity profiles from 2004 (halogen) and 2019 (halogen and LED) headlights in the forward direction, as a function of the vertical angle (*14,15*)

The curves in **Figure 4** suggest that in 2019, headlights seemed to be producing higher intensities just below the horizon than they did in 2004, and that the gradient near the horizon (with a vertical angle of 0°) has become "sharper" with a greater slope. Referring to **Figure 2**, the "hot spot" angular region of higher intensities has increased in both height and intensity value. Interestingly, the differences between halogen and LED headlights according to the market-weighted intensities in **Figure 4** are quite small in magnitude compared to the difference between 2004 and 2019 model year vehicles. Why then might drivers single out LED headlights if both halogen and LED lighting have similar distributions?

Spectral Distribution (Color)

As mentioned previously, LED headlights with CCTs exceeding 5000 K look very different from halogen headlights with CCTs around 3000 K. Not only is the "bluer" appearance of LEDs very noticeable, light sources with more "blue" or short-wavelength content appear brighter, even when a light meter reports that they produce the same intensity or photometric quantity as "yellower" or "warmer" sources such as halogen lamps. Not only will the road look brighter under LED headlights (*6*), but the lights themselves will also look brighter, and they will produce more discomfort when drivers view them (*16,17*). It should be noted that white LEDs are available in a wide range of CCTs from 2700 K to 6500 K (*18*); there is no technical limitation preventing LEDs with lower CCTs similar to those of halogen lamps from being used in vehicle headlighting systems.

Luminance

As mentioned previously, the shift from sealed-beam headlights with a small number of available shapes to headlights with replaceable light sources, to LED arrays in a wide variety of shapes and sizes has increased the styling options for headlights dramatically in recent years (*19*). A characteristic of LED lighting technology is that efficient optical systems can be designed around these compact, high-luminance sources resulting in headlights having relatively small sizes in some instances. A smaller sized-headlight producing the same luminous intensity as a larger headlight will produce a similar pattern of light along the road as the larger headlight, but its maximum luminance (in cd/m^2) will be higher. It has been shown that for light sources with an apparent angular size greater than 0.3° in diameter, light sources producing the same amount of light at an observer's eyes but having different size/maximum luminance characteristics will not be judged equally in terms of discomfort glare (*20,21*).

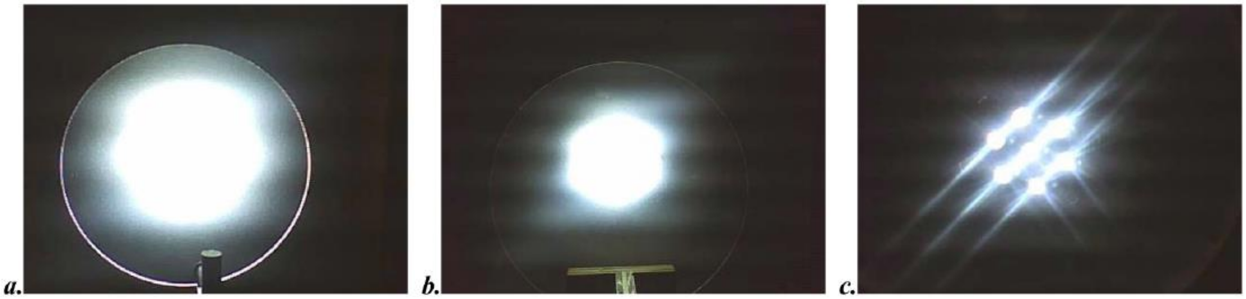

Figure 5 An LED array with a diffuser at different distances resulting in different apparent sizes and maximum luminances (a: 15,000 cd/m^2; b: 50,000 cd/m^2), and the array without a diffuser so that the individual high-luminance LEDs are directly visible (c: 1,000,000 cd/m^2)

For example, the LED arrays and diffusers in **Figure 5** will produce similar luminous intensities toward an observer but the maximum luminance is highest for the bare LED array with the smallest apparent luminous size, and observers will judge the bare LED array as being more uncomfortable to view. This effect of maximum luminance is only observed when the size of the light source being viewed is sufficiently large (at least 0.3^o in diameter). For a headlight viewed at a distance of about 150 feet along the road, the headlight would have to be more than nine inches in diameter, larger than almost all automotive headlights, in order for its maximum luminance to influence discomfort glare. In a study of discomfort glare from differently-sized headlights viewed from 150 feet away (all less than six inches in diameter), none of the different sizes resulted in differences in rated discomfort (*21*). Still, it might be possible in some situations, such as heavy traffic, for headlights to be viewed at short enough distances (possibly through rearview mirrors) that their maximum luminances could contribute to discomfort glare.

Mounting Height

One trend in the U.S. vehicle fleet in recent years that contributes to discomfort glare is the mounting heights of headlights. The photometric requirements for low- and high-beam headlights (*3*) are made with reference to the headlight location. Referring to **Figure 4**, a headlight that is mounted higher from the ground surface is more likely to expose high intensity illumination to an oncoming driver, such as if the headlight is on a pickup truck or sport-utility vehicle (SUV) and the oncoming driver is in a passenger sedan. **Figure 6** shows trends in the mounting heights of vehicles tested for safety by the Insurance Institute for Highway Safety (IIHS) in for model years 2015-16 and 2023-24. In less than a decade, the average headlight mounting height has increased by 7 cm, a highly statistically significant difference (p<0.0001, Student's t-test).

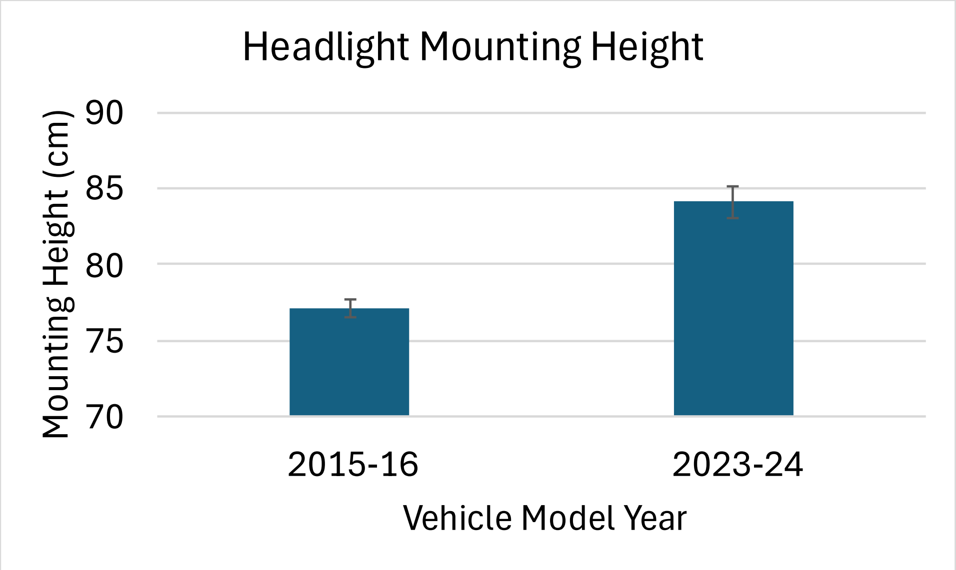

Figure 6 Average (+/- standard error of the mean) headlight mounting heights in 2015-16 and in 2023-24 model year vehicles (Source: techdata.iihs.org)

Headlight Aim

Given the very large difference in luminous intensity values produced by headlights above and below the horizon (a vertical angle of 0°) that is illustrated in **Figure 4**, it is critically important for headlights, particularly low-beam headlights, to be aimed properly, so that the horizontal gradient visible in **Figure 2** is aimed at the horizon. Yet this is often not the case, in practice. A survey of headlight aim carried out in 2008 revealed that about 60% of all of the in-service vehicles measured had at least one headlight that was misaimed in the vertical direction, either too high or too low, by 0.75° or more (*22*). It might be expected that new vehicles would have better aim than vehicles operated for several years, and this does seem to be the case (*22*).

However, headlights on new automobiles are still not necessarily very well aimed. Referring to the same vehicles tested by IIHS in terms of mounting height, there was a rather large range of headlight misaim in the vertical direction in 2015-16 model year years (**Figure 7**). Further, while there appears to have been some improvement in 2023-24 model year vehicles, there is still a relatively large spread, and the slightly improved aim is not statistically significantly different from the earlier period (p=0.49, Student's t-test). Importantly, despite the majority of vertical misaim being in the downward direction, a non-negligible proportion of headlights are misaimed in the upward direction (**Figure 8**).

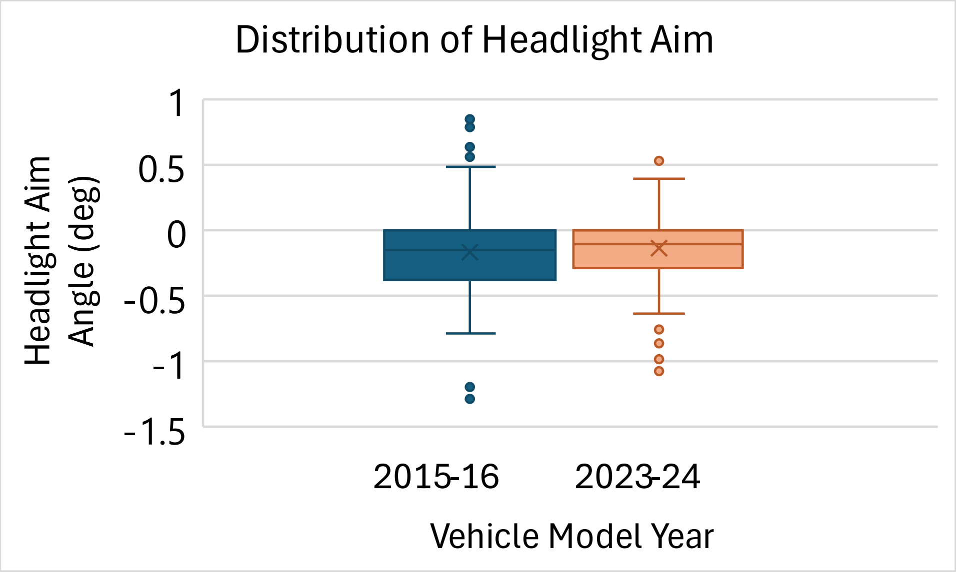

Figure 7 Distribution of vehicle headlight vertical misaim in 2015-16 and in 2023-24 vehicles (Source: techdata.iihs.org)

The role of headlight vertical aim is a major determinant of the amount of light reaching the eyes of other drivers, not only on straight, flat roads, but also along changes in vertical elevation and due to variations in vehicle pitch caused by vehicle loads. It should be noted that the regulation of vehicle headlight aim occurs at the state level in the U.S. and is not part of FMVSS 108 regulations (*3*). In countries that adhere to United Nations regulations for vehicle lighting, automatic headlight-leveling systems that maintain the vertical aim angle of headlights will become mandatory on passenger vehicles beginning in 2027 (*23*).

DISCUSSION AND CONCLUSIONS

From this brief review of headlight glare and the factors that may be contributing to the persistent complaints among the driving public about glare, it is clear that there is no single "simple fix" for headlight glare. Discomfort glare in particular has many interacting causes. Many have speculated that while discomfort glare from headlights is a nuisance, it is difficult to find a direct cause-and-effect relationship between headlight glare and an increase in crashes. While pedestrian fatalities at night have increased in recent years (*24*), the extent to which this increase has been caused by glare, as opposed to, for example, distraction from mobile devices, is not well understood. What is known is that driver behavior does change in response to discomfort glare in a manner similar to the way it changes when drivers are in situations with higher crash risk (*25*). Regardless, hardly anybody would say that the present situation with headlight glare is acceptable. So, what can be done?

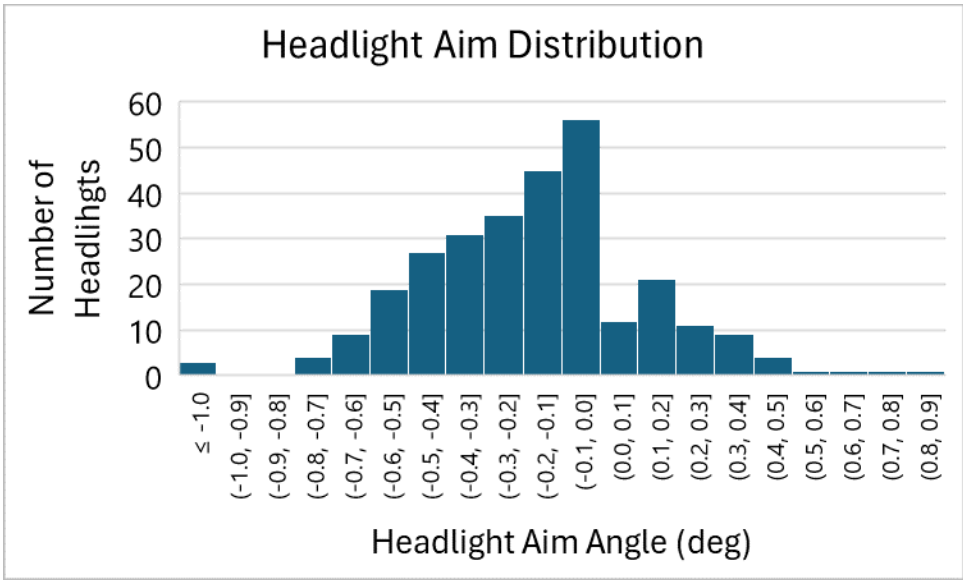

Figure 8 Histogram of vertical misaim angles observed overall in 2015-16 and 2023-24 vehicles (Source: techdata.iihs.org)

Color Limits

Drivers have used “warm white” filament sources on their vehicles for decades. “Warm white” LEDs are available and have similar efficacies as those with higher CCTs. It could be argued that replacing high-CCT LEDs with lower CCTs around 3000 K might reduce complaints about headlight glare because this would remove the most obvious difference between halogen and LED headlights. Perhaps this is true, but whether there might be any drawbacks to such a transition is also not well understood. Illumination with greater short-wavelength content can improve detection of objects seen in the visual periphery under low, mesopic light levels (*26*); possibly, high-CCT LED headlights could better help drivers see potential hazards off the roadway edge.

Mounting Height Limits

The prevalence of SUVs and pickup trucks on the roadway is unlikely to change in the near future. Could the styling for these vehicles be modified in such a way that lower mounting heights for their headlights would be practical? Of interest, such a modification would have potential advantages for visibility in fog and snow as well (*27*) by moving the headlights farther from the driver’s line of sight and reducing the brightness of light back-scattered from fog droplets and snowflakes.

Overall Maximum Intensity Limits

As illustrated in Table 1 and Figure 1, low-beam headlights are required to meet several minimum and maximum luminous intensity requirements in several specific angular directions from the headlight. Figure 4 suggests that luminous intensities have increased overall in recent years, and in many angular locations there are no specific intensity limits. An overall maximum luminous intensity for low-beam headlights could help to ensure that oncoming drivers would not be exposed to intensities more similar to those of high-beam headlights.

Adaptive Driving Beam

Perhaps the most promising development for the reduction of headlight glare is the potential for adaptive driving beam (ADB) systems to simultaneously improve driver visibility and reduce glare (*28*). ADB systems use dynamic arrays of LED headlighting sources in conjunction with cameras and sensors, so that a driver can use high-beam levels of forward illumination at all times. When an oncoming or preceding vehicle is present, the cameras and sensors direct the lighting system to reduce the intensity from the headlights specifically in the direction and location of the other vehicle. As a result, the other driver sees what appears to be “low-beam” headlight intensity while the driver with the ADB headlights can take advantage of having “high-beam” levels of illumination throughout the rest of the roadway. These systems have been approved for use in countries adhering to United Nations vehicle lighting regulations for more than a decade, and since February 2022 have been approved in the U.S., albeit according to a very unique and complex (*29*) FMVSS 108 regulation (*3*) that has not yet resulted in widespread use on U.S. roads.

If the complexity of this regulation can be overcome, ADB systems will help overcome issues related to glare and headlight misaim and mounting height, because the cameras and sensors use real-time information to determine where to reduce the intensity of the headlights; if the overall system's alignment changes over time due to "wear and tear" the cameras will be able to adjust which portion of the LED array needs to be dimmed in order to minimize glare to oncoming and preceding drivers.

Despite the potential promise of ADB to dramatically alter the situation with headlight glare, ADB systems will not be inexpensive, at least for some years after they are first introduced in the U.S. In the meantime, transportation agencies, researchers and the driving public will need to address headlight glare in a more piecemeal manner. It is hoped that the concepts and data presented in this review can be a useful part of a dialogue leading to action on behalf of drivers anxious for an end to headlight glare.

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AUTHOR CONTRIBUTIONS

The author (J. Bullough) confirms that he is solely responsible for the writing of this manuscript.

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