Title

Photometric Insights Gained from Watching an Audi

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Photometric Insights Gained from Watching an Audi

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Background: This paper will describe an encounter with, and a look at, an Audi. Observations and measurements of the output of its headlights serve to emphasize some things concerning the relation of photometry to its task. Photometry's task is to predict the visual effect of light.

This paper focuses on what photometry can't tell us about the effect of a light source on the eye. The eye has capability and idiosyncracy that photometric specifications cannot anticipate.

First, we introduce a problem that has vexed drivers and safety officials alike. It's that the new High Intensity Discharge (HID) headlights are said to be bothersome to people who have to look at them. Then, we describe a bit about those lights, and their predecessors.

While the major interest at this meeting is not in surface transportation matters, that is where this problem resides. Consideration of this problem does, however, supply some lessons that are worth thinking about. Because lights in the air still have to be interpreted by the same nervous system, and it's in the nervous system that the interesting things seem to happen.

Headlight evolution:

- Early twentieth century:
  oil lamp
  then tungsten bulb
  then sealed beam self-contained units

- Mid-1980's: Federal regulations relaxed
  Replaced by 17 point luminance specification
  Halogen (tungsten)
  High **I**ntensity **D**ischarge (HID)

Here's a quick tutorial on these lamps and the tungsten halogen ones that they replace.

Figure 1 shows schematics of halogen and HID lamps. Halogen is shown on the left. It contains a tungsten filament. The halogen gas, bromine and iodine, helps to prevent sublimated tungsten from being deposited on the inside of the glass envelope as occurs in traditional tungsten lamps. The spectrum of this lamp is typical tungsten, it is continuous with highest power at the longest wavelengths.

HID is shown on the right. A very high driving voltage (maybe 10,000 volts) causes an arc discharge from one electrode to the next. This arc gives a line spectrum, much like that of a fluorescent lamp. Power is typically high near 470 and 580 nm.

Complaints:

- Annoying
- Momentarily blinded (...like arc welder)
- …like looking at bare spot lamp
- …gave me a headache

Ricardo Martinez (former NHTSA Administrator) is quoted as having these observations:

- "...solution for you, problem for others"
- real question is "why?"
- they don't exceed our maximum standards
- something in the physics of light…"

Annoyance is a subjective appraisal that is not easily quantified. Consider the Cohn family computer on which this manuscript is being prepared. The D drive contains downloaded music, placed there by younger members, who stated that they liked this genre that they refer to as 'music'. Thus it is that on the D-drive one can find artists named Eminem, Dr. Dre and so on.

Subjectively speaking, I find this annoying.

Subjectively speaking, members of my family, don't find this annoying. At least that's what they say. And to judge by what they do, which is to say listen to it, I would guess that they don't. The pertinence here to annoying headlights will become more apparent at the end of the paper.

Theories to Explain the Annoyance:

In what follows, please note who is authoring the explanatory hypothesis and then where they think the fault lies.

Ricardo Martinez, a physician, says the problem lies in the physics.

Michael Janoff, a respected engineer, puts the problem in the brain, where color is interpreted, noting that subjective tests reveal that some color HIDs are less annoying than others.

Peter van Westering is the market development manager for Philips Lighting. He ascribes the problem to too much looking[1].

Do we see a pattern here?

Janoff also points out that the light meter used in government tests that determine if a source falls with the limits set by standards, is predicated on day (photopic) vision. But at night, when the annoyance occurs, both rods and cones are involved, and this might cause a source with a lot of blue to measure brighter.

Folks at UMTRI agree with his assessment saying this causes discomfort glare[2].

Where are HIDs found?

In the 2000 model year one could find these on the Acura, Audi, BMW, Infinity, Lexus, Lincoln, Mercedes, Pontiac, and Porsche, to name several.

Finding a Very Annoying Example:

The authors surveyed the passing vehicle population during evening hours and then met to agree on the most egregious example of headlight annoyance. Our group of four observers determined that the Audi fell right in this category, so we rented a 2000 model A4. We parked it in a covered garage where lighting was dim though not absent.

We had to elevate the front end of the Audi on wooden pallets so as to accommodate the height of the tripod which held our photometer.

Photometry: Luminance [cd/m.sq.] of the source at about 34 ft was taken using a Minolta Chroma Meter CS-100 at successive 3.5" height increments at each of three distances from the projected centerline of the car. Colorimetry with the same instrument gave X,Y color coordinates.

We focused our instrument on the driver's side headlight and simultaneously measured the luminance and the color.

Tenets of Photometry:

Photometry is really modeling. It yields a predicted effect on the eye of a given light pattern. The prediction begins with the power at each wavelength and weights this power by an estimate of the ability of the photoreceptors of the eye to transduce energy at a given wavelength. (The photoreceptor which performs this function cannot know the wavelength of any photon that stimulates it – it can only know that a photon was caught in photopigment). Weights are chosen either to reflect the properties of night vision (rods) or of day vision (cones) and the weights come from an average of measurements made on a small sample of observers some years ago.

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[1], M.L. Wald, "Brighter idea that some eyes are finding too bright" New York Times, 10/20/99

[2] "Joint effects of wavelength and ambient luminance on discomfort glare from monochromatic and bichromatic sources.UMTRI Technical Report 91-42, M. F. Flanagan, M. Sivak and A. W. Gellatly

In Figure 2 we see the spectrum of an HID and of a tungsten halogen lamp in the upper panel. The lower panel shows the V_λ and V_λ' functions which express those weights that determine, at each wavelength, what fraction of the available energy would participate in forming a sensation. In theory, one simply multiplies the spectrum by the filter function and sums over all wavelengths to get an answer. In practice, some photometers have the weights built-in, sometimes in the form of a light filter.

Let's go back to our experimental set-up. Figure 3 shows a schematic of what one would have seen had one stood on the rear bumper of the Audi A4 and faced forward.

The headlights illuminate a broad area to the front. The pattern of illumination, which derives from both headlights, is low to the side facing traffic and higher toward the curb side. The transition from the brightly lit zone to the nearly unlit zone is very sharp. At the transition there is a clear color change as illustrated here. The color moves from whitish below through orange and then to bluish above and finally to grey.

Before describing our observations and measurements, consider the X, Y space for colored lights. As a reminder, spectral lights, that is to say lights of a single wavelength, arrange themselves around the horseshoe-shaped perimeter on the so-called 'spectrum locus'. Reds occupy the lower right corner. Proceed counterclockwise around passing through orange, yellow, green and then blue and violet toward the lower left.

The SAE has defined a zone that they label 'white' in this space. It occupies an irregular figure in the middle of the horseshoe.

Figure 4 shows our measurements in the X,Y coordinates. The SAE white zone is also shown here. Our measurements are taken at the top of the bright zone and proceed upwards towards the dark zone. Thus we started on the orange side of white and moved toward the blue.

Measurements on the upper right in X,Y space were taken at the bottom of the transition region where the white is sort of orange. Those on the left, in the region of bluish white, occur at the uppermost reaches of the zone between bright and dim. Measurements in the dim zone go back to a more even white.

Error in the instrument with which this measurement is made, makes it prudent not to conclude that the headlight falls outside of the SAE white zone, but it certainly may, especially where it appears bluish.

Whether it does or not, that the color is different as seen from different vantage points is an important part of the story here.

<u>MacAdam Ellipses:</u>

David McAdam published a very thorough study of the ability to discriminate color. This is a more general endeavor than that of quantifying wavelength discrimination, or the difference in wavelength needed in order for two wavelengths to be seen as different. Most colors that we see are not pure saturated single wavelengths -- they're not monochromatic. They contain a spectrum. One can assess the ability to see two colors as different by taking an arbitrary color and testing to see which colors are just noticeably different. Macadam[3] showed the result of his study in the X,Y coordinate system. There, picking the first color amounts to selecting any x,y pair within the space. Then one moves away from the x,y that was initially selected until a new pair, x',y' is just detectably

[3] Macadam, D. J. Opt. Soc. Am.247-2764, 1942

different. Plotting the family of all such colors turns out to trace an ellipse in the color space with the center at the original point. It will be no surprise to those of you who have seen HID headlights that the white which is orangish is very different and easily seen as different from the white that is bluish. In other words, the different colors emanating from the HID are clearly subjectively different.

Macadam ellipses (Figure 4) would appear to show that the different extremes of white can appear to be just different as they are just about the size of the SAE white zone and are similarly oriented. In fact, the ellipses have been deliberately distorted. They are 10 times the size that they should be, which means that there are several different shades of white in these lamps, each distinguishable from all of the others.

Summary of Color Observations:

- The HID color roams freely around the SAE 'White' zone.
- Where it looks blue, it may lie outside that zone.
- There is a systematic progression from orangish white to bluish white.
- The color on the right headight may differ from that on the left.

Luminance measurements were obtained in the same way, and at the same time, as the color measurements. To remind: We measured luminance looking directly at the left headlight with our photometer. We looked at it from 18 different points in the field of view. These were close to the zone where the eye of an oncoming driver might be found.

In the graph of Figure 5 we plot luminance on the vertical axis. The x-axis is for elevation within the field of view. Each unit on that axis is three inches. Thus, in only nine vertical inches we find a factor of ten difference in brightness. The z-axis on this graph is distance across the field of view. Here we separated our measurement sample tracks by 10 inches and then by 15 inches. The interesting finding is that a factor of two difference can be found in 10.5 inches horizontal separation

Thus, we find static differences characterizing the HID lights:

- They are brighter, (but no more than the federal limits according to NHTSA).
- The light can appear to be coming from a more concentrated source.
- They are bluer.
- They are differently colored depending on viewing angle and location.

(We observed additional differences between the left and the right).

Simulating Real World Observations:

Of course, there is a marked difference between the conditions of our test and the conditions one encounters while driving, or while the car that you are observing is moving.

It seemed necessary to study these. And in doing so we immediately depart the realm of photometry, because photometry describes the effects of static sources.

What we were trying to recreate here was the look of an Audi in flight. Ideally we would have placed the vantage point in flight as well, but that was discouraged by the owner of the video camera.

At this point one should look at a brief clip of the video hat we used record our observations under dynamic conditions (http://spectacle.berkeley.edu/~tecohn). What you will see is that the two headlights appearing to move slightly up and down. They are actually moving very little but the angle that they make with respect to the camera is changing, not by much, but with profound visual effects.

For this exercise we placed the camera right in the critical zone where color is varying and where luminance is also.

When headlights were viewed frontally, vehicle motion (up/down generated by time varying weight – at roughly 1 Hz -- on the rear bumper) leads to the impression that headlight brightness differs in the two, so does headlight size, and the difference goes back and forth over time. The same holds for color.

Observations:

- Color changes in time
- This is different at each headlight
- Luminance changes in time
- Also different at each light

What does this do to the eye? Or better yet, how does the eye react?

Here we need to point out some pertinent visual phenomena (neither predicted by, nor encompassed within photometry)

- Binocular luster
- Spatial contrast
- Temporal contrast of luminance
- Temporal contrast of color
- Apparent motion of contrast
- Apparent motion of color

Binocular Luster: This was first reported by Helmholtz[4]. It requires different color or luminance to the two eyes. It results in a sensation of luster - rare and certainly not usually associated with headlights. According to our observations, it could occur as eyes are typically separated by nearly three inches.

Spatial contrast:

The discovery of the spatial contrast function of the eye is now nearing a half century old. Its simple message is that uniform luminance is far less persuasive to visual neurons than is luminance concentrated in small regions. In other words, under most conditions, foveal vision is bandpass, not low pass[5]. HID lights would be more sensitivity seen at a given luminance than would traditional headlights. On those occasions when the viewing angle results in a smaller looking light, it will be seen that much more sensitively. And this would be true at observation distances as large as 400 feet. Even so, photometry implicitly assumes a very different model of visual behavior, that of simple spatial integration.

Temporal contrast:

The temporal contrast story is a close analog of the spatial contrast story. Things whose luminance changes in time will generally be better seen than static light patterns. Temporally speaking, foveal vision is bandpass in time[6].

Photometry would not predict this, as it describes only the effects of unchanging patterns of light.

Apparent Motion:

Now if your intuition tells you that changes in space combined with changes in time would be even more compelling, you're absolutely right. And that brings us to the last two possible explanations of the annoying effects of HID lights that we have been able to discern.

The conditions for apparent motion:

Closely space stimuli, similar in shape, occurring in temporal proximity

What one sees:

[4] J.P.C. Southall, Ed., Helmholtz's Treatise on Physiological Optics (Optical Society of America, 1925), vol. 3, p.525, (reprinted by Dover, New York, 1962, p.515.

[5] O. H. Schade, (1956) Optic and photoelectric analog of the eye, J. Opt. Soc. Am., 45, 721-739.

[6] De Lange, H. (1958) Research into the dynamic nature of the human fovea-cortex system with intermittent and modulated light, J. Opt. Soc. Am., 48, 777-784.

Something moves from one place to another

Application

an extra amount of light goes from one HID to the other -- sometimes a colored blob does so, and the two phenomena can be independent.

Here's an example: at several points on the video, one can see one headlight dim as the other one brightens. The visual nervous system, under some conditions, interprets this to mean that a source of light moved from the initially bright spot to the subsequently bright spot. That interpretation runs up against the certainty with which our brain trusts that the oncoming car has no such capability, that its headlights are rooted in metal and do not move. This could cause annoyance or discomfort.

A related situation occurs for a color change that appears at one spot then at another. The brain interprets that as the movement of a colored blob from one spot to the other.

Importantly, brain circuitry to see movement is far more sensitive, and far faster to report what's going on, than circuitry to report the amount of light that's out there. So those responses will tend to dominate our impression of the oncoming car.

Conclusion:

Our conclusion is, that HID headlights are a bit like modern music. Some people are annoyed by them while others will be entertained. A number of features of these lights have been described which set them apart from conventional headlights. Some static features, including color and luminance, and occasionally a smaller apparent size, and their spatial dependence, are adequately described by traditional photometric measurements. But key reasons for their novel appearance can only be described by resorting to understanding of the ways in which the visual nervous system departs from the simple light integration that is assumed in photometry.

Countermeasures: While we have only pointed to tenable hypotheses in this study, and while we have not demonstrated in a given instance that annoyance (or headache or any other response) can be causally linked to any particular visual quality of HID lights, one might nonetheless ask how to minimize the 'light show'. Two clear strategies emerge. The first is to alter the optics so as to minimize color *change* at different viewing angles. The next is to alter the rate of luminance *change* with viewing angle. Both we have the effect of minimizing those aspects of the lights that are unique.