

Subjective and Objective Effects of Driving with LED Headlamps

Michael Flannagan
University of Michigan

Mitsuhiro Uchida
Stanley Electric Co., Ltd.

John Michael Sullivan and Mary Lynn Buonarosa
University of Michigan

ABSTRACT

This study was designed to investigate how the spectral power distribution (SPD) of LED headlamps (including correlated color temperature, CCT) affects both objective driving performance and subjective responses of drivers. The results of this study are not intended to be the only considerations used in choosing SPD, but rather to be used along with results on how SPD affects other considerations, including visibility and glare.

Twenty-five subjects each drove 5 different headlamps on each of 5 experimental vehicles. Subjects included both males and females, in older (64 to 85) and younger (20 to 32) groups. The 5 headlamps included current tungsten-halogen (TH) and high-intensity discharge (HID) lamps, along with three experimental LED lamps, with CCTs of approximately 4500, 5500, and 6500 K. Driving was done at night on public roads, over a 21.5-km route that was selected to include a variety of road types. Vehicle instrumentation was used to derive the measures of objective driving performance. After driving, subjects completed a set of subjective ratings.

The objective driving measures varied strongly with road type, but showed little if any effects of headlamp type. The subjective measures showed strong differences between the TH and HID lamps, but only small differences among the LED lamps related to CCT. There was a small tendency for higher CCT to result in more positive subjective ratings. Overall, the results indicate that effects of CCT on objective and subjective variables are not strong relative to the range of differences associated with roadway type.

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INTRODUCTION

The primary purpose of this research was to understand the effects of the spectral power distribution (SPD), or color, of LED headlamps on driver behavior and comfort. All headlamps are required to be in a certain range of white, but nominally white LEDs offer a range of color options, from relatively low correlated color temperature (CCT) (yellowish) to relatively high CCT (bluish).

Given the option of choosing a color for LED headlamps, it is important to investigate the considerations that may be affected by that choice. These considerations include subjective preferences of drivers and possible effects on objective driving performance. Both subjective and objective considerations were investigated in this study.

One of the main reasons that headlamp color may affect objective driving performance is illustrated in [Figure 1](#). This figure illustrates the different spectral sensitivities of human day vision (photopic vision, using cone receptors) and night vision (scotopic vision, using rod receptors). As lighting conditions decrease from daytime levels to nighttime levels, human vision becomes more sensitive to short wavelength radiation. The approximate range over which this takes place is illustrated in [Figure 2](#).

In nighttime roadway conditions, drivers are exposed to a full range of lighting conditions, from high photopic levels to low scotopic levels. The highest levels are from active light sources such as the images of signaling and marking lamps, or even oncoming headlamps. The lowest levels are nearly dark, at the periphery of the illumination from headlamps. The road surface

near a vehicle is often in the mesopic range. Adding to the complexity of the lighting conditions faced by a driver at night, the driver's eyes are normally moving rapidly and often across the road scene. The state of light adaptation of the driver's eyes will also be complex, with multiple adaptation levels in local areas of the retinas because of the varying recent history of light exposure in those local areas. Probably, the centers of the retinas will usually be adapted to higher light levels and the peripheral areas of the retinas will be adapted to lower levels. This is because of both the concentration of headlamp illumination in the center of the roadway scene and the concentration of visual fixations in the same area.

Because light sources differ in SPD, their relative visual effectiveness may change from high, daytime light levels to dark, night levels. For example, if several light sources are all equated for daytime conditions, and some of those light sources have more short wavelength (bluish) content, then the

bluish sources will be seen as brighter at nighttime light levels. This change is captured in photometry by the scotopic/photopic (S/P) ratio. The S/P ratio indicates how different light sources would be expected to appear at night if they are all equated for daytime conditions. The S/P ratios for the five types of headlamps involved in the present study are shown in [Table 1](#).

Daytime driving involves virtually only photopic vision, but nighttime driving may involve both photopic and scotopic vision. The possible role of scotopic vision in night driving has not been determined, and it may be that most object recognition (e.g., seeing pedestrians) involves little if any scotopic vision, while other visual functions (e.g., perceiving the course of the roadway) involve a more significant scotopic component. Because the relative roles of the two visual systems are not clear, it is worthwhile to investigate empirically the possible benefits of headlamps with differing SPD.

Table 1. The scotopic/photopic (S/P) ratios for the five types of headlamps in this study.

Headlamp	S/P ratio
Tungsten-halogen (TH)	1.52
High-intensity discharge (HID)	1.72
LED 4500	1.51
LED 5500	1.73
LED 6500	1.98

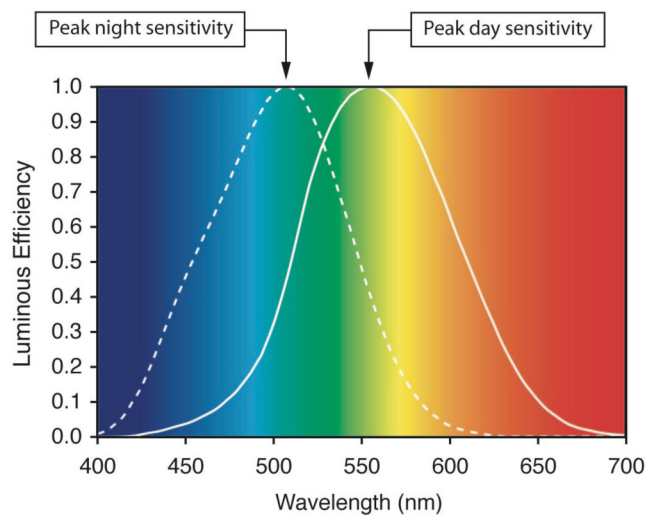


Figure 1. Spectral sensitivity of human vision at daytime (photopic) and nighttime (scotopic) light levels.

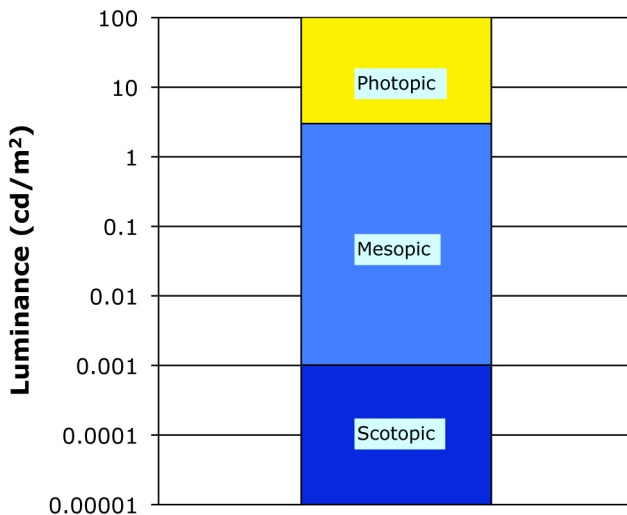


Figure 2. The approximate ranges of luminance over which human vision is photopic, mesopic, or scotopic.

HUMAN FACTORS EFFECTS OF HEADLIGHTING

The design of headlamps is affected by many considerations, including how headlamps support the ability of the driver to detect important targets (primarily pedestrians), and how headlamps affect oncoming drivers (in terms of discomfort and disability glare). The present study was designed to address some, but not all, of the considerations that should be taken into account in designing headlamps. The issues addressed here are how SPD of headlamps (which includes other aspects of color, such as correlated color temperature, CCT) affects objective driving performance and subjective evaluations by drivers.

The evaluation was done under conditions that were as close to normal driving as possible, given the experimental context: Randomly selected drivers with no special knowledge of headlighting were asked to drive on public roads at night. The roads were selected to include a variety of road types, including low-speed residential, medium-speed rural, and high-speed expressway. The drivers were simply asked to drive as they normally would, and they were not told any details about the questions addressed by the study. Although the vehicles used were instrumented to record many aspects of driving performance, care was taken to make them appear very much like normal passenger cars rather than experimental vehicles.

The measures of objective driving performance were designed to indicate how headlighting might affect various important aspects of driving that are probably influenced by visibility of the roadway itself, including control of speed and lateral position. But they were not intended to include detection of unexpected targets in the roadway (e.g., seeing pedestrians along the road edge).

Objective driving performance was measured by a large set of instruments installed on the vehicles. The measures included basic control of the vehicle, in terms of speed and lateral position, as well as an experimental measure of driving workload that has been used in several earlier studies [1, 2]. The measure is intended to assess how difficult driving is by analyzing the continuous steering-wheel control movements by the driver and quantifying the ratio of spectral power in one band of that signal (power from 0.3 to 0.6 Hz as a proportion of power from 0.1 to 0.6 Hz). The measure is based on studies of steering behavior that suggest that a peak in power from 0.3 to 0.6 Hz is related to compensatory steering movements [3]. Higher proportions of power in that band are believed to reflect more difficult driving, as may be the case if road illumination and road visibility are too low.

Subjective ratings of headlamp performance were made using scales from previous studies. General headlamp performance ratings were made using a 12-item form based on earlier work [4], and subjective workload was measured using a standard 6-item form, the NASA Task Load Index (NASA-TLX) (<http://human-factors.arc.nasa.gov/groups/TLX/>).

METHOD

Headlamps

There were five headlamp types to be tested, as shown in Table 2. Figure 3 provides a rough overall comparison of the beam patterns of the five lamp types, in terms of photometric intensity at three reasonably representative test points (2° down, 9° left; 1° down, 2° right; 2° down, 9° right). The values in Figure 3 are averages for the left and right headlamps of each type, which were similar to each other in all cases. Overall, in terms of light output, the tungsten-halogen (TH) headlamps were lowest, the high-intensity discharge (HID) lamps were intermediate, and the three LED lamp types were collectively highest. As was intended, there are no major differences among the three LED lamp types in terms of light output or beam pattern. Comparisons among the LED lamps should therefore reflect virtually only differences in SPD, whereas comparisons involving the TH and HID lamps may reflect differences in light output as well as in SPD.

Table 2. The five headlamp types used in the current study.

Source type	Nominal CCT (K) (actual)
TH	(3082)
HID	(4177)
LED	4500 (4335)
LED	5500 (5356)
LED	6500 (6658)

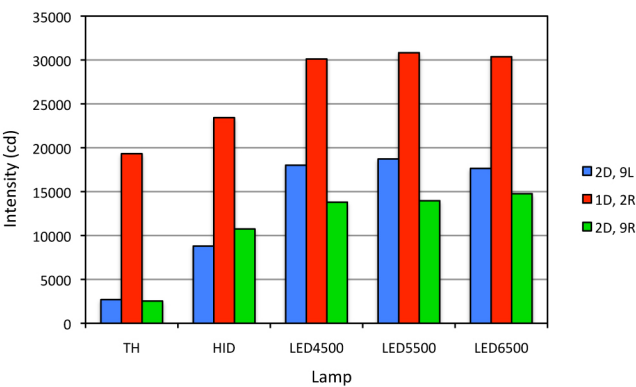


Figure 3. Intensity at three locations for each of the five headlamp types.

Test Vehicles

Five identical 2007 Honda Accords were used. All vehicles were instrumented for a variety of measures. The measures of most interest for the current study are listed in Table 3. Because the vehicles were developed for a large field test of safety systems [5], the instrumentation package was elaborate, and included many variables that were not of direct concern for the present study, but which may provide opportunities for later analysis.

Although the vehicles were nominally identical, to insure that any minor differences that might exist among vehicles would not be confounded with the five headlamps, the installation of the lamps on the vehicles was changed between daily sessions so that each type of headlamp was used equally often on each experimental vehicle.

Table 3. Selected instrumentation measures for test vehicles.

Measure	Description
GPS position	Latitude and Longitude, sampling frequency 10Hz
Speed	Current speed, sampling frequency 50Hz
Steering	Steering wheel angle, sampling frequency 50Hz
Lateral position in lane	Lane tracking by foreground camera
4 video cameras	Driver face, cabin view, light and left rear side

Test Route

The test route consisted of public roads in and near Ann Arbor, Michigan. The route was a 21.5 km loop that began and ended at the UMTRI building. The course is illustrated in Figure 4.

As shown in the figure, seven road segments were selected to be used in analyzing driving behavior (speed and lateral control). The segments did not include major intersections, and so would normally involve continuous driving, without stopping, starting up, or turning. Table 4 gives descriptions of those seven segments. Also shown in Figure 4 are nine shorter

sections of road in which there were significant curves. Those sections were selected to be used in analyzing driving behavior in curves.

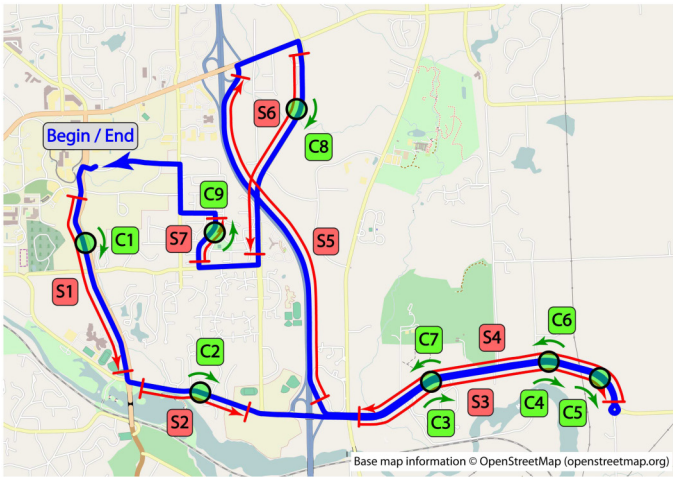


Figure 4. The experimental test route (blue line), with the locations of the road segments (red lines, labeled S1 through S7) and curves (green dots and arrows, labeled C1 through C9) at which driving behavior was analyzed.

Table 4. Description of each segment in the test route

Segment	Description
1	Medium speed with a wide field of view and moderate traffic.
2, 3, 4	Medium speed, with a narrow field of view because there are many trees along the road. Traffic is light. There are many curves and hills.
5	High speed, with a wide field of view and moderate traffic, mostly gently curves.
6	High speed, with a wide field of view and light traffic, mostly gentle curves.
7	Low speed, residential, narrow fields of view.

Subjects

The study involved 25 total participants. All were licensed, active drivers. There were 13 in an older group, including 7 males and 6 females (ranging from 64 to 85 with an average age of 70.1). There were 12 in a younger group, including 6 males and 6 females (ranging from 20 to 32 with an average age of 24.8). All subjects had normal visual acuity and color vision.

Subjective Rating Scales

Three forms for subjective ratings were used. A 12-item set of general headlamp performance items and the NASA Task Load Index (NASA-TX) (<http://humanfactors.arc.nasa.gov/groups/TLX/>) were used after each of the five individual test drives for the five headlamps. A third form, which asked subjects to indicate which of the five headlamps they liked best and least, was used only once per subject, at the end of the driving session. The subjective rating forms are included in the Appendix.