

Does LED Roadway Lighting Affect Driver Sleep Health?

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Above: Traditional high-intensity discharge (HID) light sources are being replaced by light emitting diode (LED) technology, but do we know the impact of these replacements? Do LEDs with high blue content influence alertness or human health? Blue light in the wavelengths common in consumer electronics—such as tablets and monitors—is known to influence the circadian system and melatonin regulation. NCHRP Project 05-23 sought to determine if this is so in the roadway environment, and how much LED roadway lighting with high blue content it might take to make a difference in nighttime traffic safety.

Light emitting diode (LED) technology has revolutionized the lighting industry. The capabilities of these light sources, like dimming and instant-on (along with their high efficiency), have allowed lighting designers to overcome some of the limitations of previous technologies, particularly in roadway lighting environments. However, concerns related to the health and environmental impacts of LEDs have been raised. An American Medical Association report expressed concern regarding the blue content in the LED spectrum and its effect on circadian rhythms in humans (1). Despite these concerns, no controlled empirical studies have quantified the health effects of any part of the LED spectrum under real-world roadway lighting conditions.

Circadian Rhythms in the Industrialized World

The human body's 24-hour circadian rhythms are driven by light in the environment. Light also has powerful neuroendocrine and neurobehavioral effects,

including the regulation of melatonin, a hormone secreted by the pineal gland. These effects are mediated in part by light stimulation of the eye's intrinsically photosensitive retinal ganglion cells (ipRGCs) (2). For healthy circadian and neuroendocrine regulation, humans need exposure to sufficiently bright light during daytime and darkness at night. In modern industrialized nations, nighttime lighting on roadways and in outdoor spaces raises concerns that it disrupts normal sleep, circadian rhythms, and neuroendocrine physiology. Such disruptions have been associated with the risk of some cancers, heart disease, and metabolic disorders (3). The ipRGCs are most sensitive to blue light, with light in the wavelength range of 459 to 484 nanometers having the strongest effects on the circadian system and melatonin regulation (2, 4). LEDs typically have higher blue spectral content than traditional high-intensity discharge (HID) light sources. Exposure to LEDs in the evening has been shown to disturb circadian rhythms, resulting in sleep loss (5–6).

By contrast, there is evidence that light with a high blue content (such as light from LEDs) can increase alertness and enhance cognitive performance in humans (7–8) and, as a result, enhance nighttime traffic safety among drivers and pedestrians. To design effective roadway lighting, there is a growing need to understand the relationships between roadway light level, melatonin suppression, and driver alertness and health. However, these relationships had never been investigated in realistic roadway environments until the research undertaken in National Cooperative Highway Research Program (NCHRP) Project 05-23, “Effects of LED Roadway Lighting on Driver Sleep Health and Alertness.” To inform roadway lighting standards that will reduce unintended negative effects of roadway lighting and improve driver alertness, it is critical to understand the effects of both spectral power distribution and light levels on human health and alertness.

The Research Effort

NCHRP Research Report 968: *LED Roadway Lighting—Impact on Driver Sleep Health and Alertness* documented the effects of different lighting types and their corneal illuminances on measures of drivers’ sleep health and alertness (9). Sleep health was evaluated based on melatonin levels in saliva. Driver alertness was measured objectively using driver reaction time, percentage of time that a driver’s eyelids are closed over a certain period of time (PERCLOS), and standard deviation in lane position (SDLP), as well as subjectively using the Karolinska Sleepiness Scale (KSS). This project filled a critical technological need by determining the effects of light type and level on driver sleep health and alertness. These results are expected to be highly relevant to the needs of state departments of transportation (DOTs) and will allow for informed, evidence-based decisions regarding light source and level.

To address the project goals, the research team conducted two experiments. The first measured illuminance dosage. The second assessed driver sleep health and alertness (DSHA).

Illuminance Dosage Experiment

The team measured the illuminance of a wide range of roadway lighting sources based on the spectral power distributions observed in realistic roadway conditions and from LED consumer devices.

For the naturalistic driving portion of the experiment, a member of the research team wore a personal light dosimeter (Figure 1) while driving an instrumented vehicle (2016 Ford Explorer) on the Virginia Smart Road, a closed test track that features lighting capabilities and other advanced research aids for transportation technology and safety research. The length of the driving portion was two hours during which the driver was exposed to different roadway lighting conditions.

In the consumer device exposure portion of the experiment, a personal light dosimeter and an illuminance meter measured the light from LED consumer devices (e.g., television, tablet computer, and mobile phone) under two separate conditions for the same duration of two hours. The experiment was conducted

in conditioning rooms where light from extraneous sources had been eliminated.

Daily exposure measurements also were recorded. Ten volunteers wore the personal light dosimeter for one day (24 hours) to determine the typical illuminance exposure received from light sources encountered on a daily basis. This task provided information on the range of corneal illuminance exposure during a typical 24-hour period.

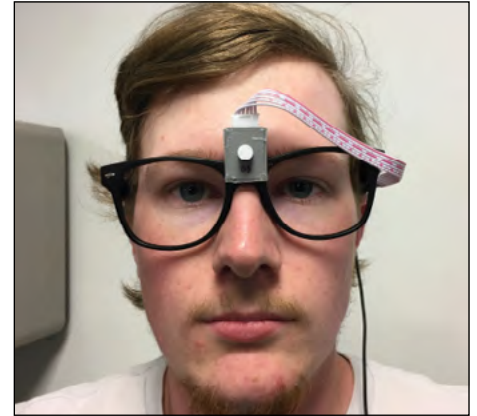


FIGURE 1 Personal light dosimeter developed at Virginia Tech Transportation Institute.



Photo: Courtesy of Rajaram Bhagavathula

Lights on and ready to roll, the vehicle (at right) is waiting to start a two-hour test run on a section of the Virginia Smart Road, one of the world’s most advanced testing facilities for transportation technology and safety research. Managed by Virginia Tech Transportation Institute in cooperation with the Virginia Department of Transportation, this facility was used extensively to carry out the LED roadway lighting experiments under controlled conditions.

Results of the Illuminance Dosage Experiment

This experiment showed that the illuminance dosages from a continuous two-hour roadway lighting exposure were considerably lower than the illuminance dosages a person experienced in a 24-hour period or from a two-hour exposure to most of the consumer electronic devices tested (Figures 2 and 3). The most common LED light source used on U.S. roadways is the 4,000 K LED and a luminance of 1.5 cd/m² (candela per square meter) is 25 percent higher than the highest light level specified by the Illuminating Engineering Society's recommended practice for roadway lighting. The illuminance dosage from a two-hour exposure to a 4,000 K LED at a luminance of 1.5 cd/m² roadway lighting condition is approximately 0.1 percent of the total illuminance dosage experienced by daytime office workers (as measured in this study with a cumulative average illuminance dosage of 14,848,272.7 lux-s).¹

The highest illuminance (amount of light falling on a surface) dosage from a two-hour exposure to 4,000 K LED at luminance (amount of light being reflected from a surface) of 1.5 cd/m² (13,162.1 lux-s or 1.9 lux/s)² was lower than all consumer electronic devices except the iPad Pro (3,456 lux-s or 0.5 lux/s) and Kindle Paperwhite (12,456 lux-s or 1.5 lux/s) in dark mode for the same two-hour duration. This comparison assumes that a person is continually driving in a lighted section for a two-hour period, which is unlikely unless drivers in major cities are taken into account. By contrast, a two-hour exposure from a consumer electronic device is a common occurrence in today's society. Further, in order to get the same illuminance dosage from a 4,000 K LED at a luminance of 1.5 cd/m² roadway lighting condition as from a two-hour exposure to a computer monitor or a television in dark mode, a person has to experience that roadway lighting condition for 17.8 and

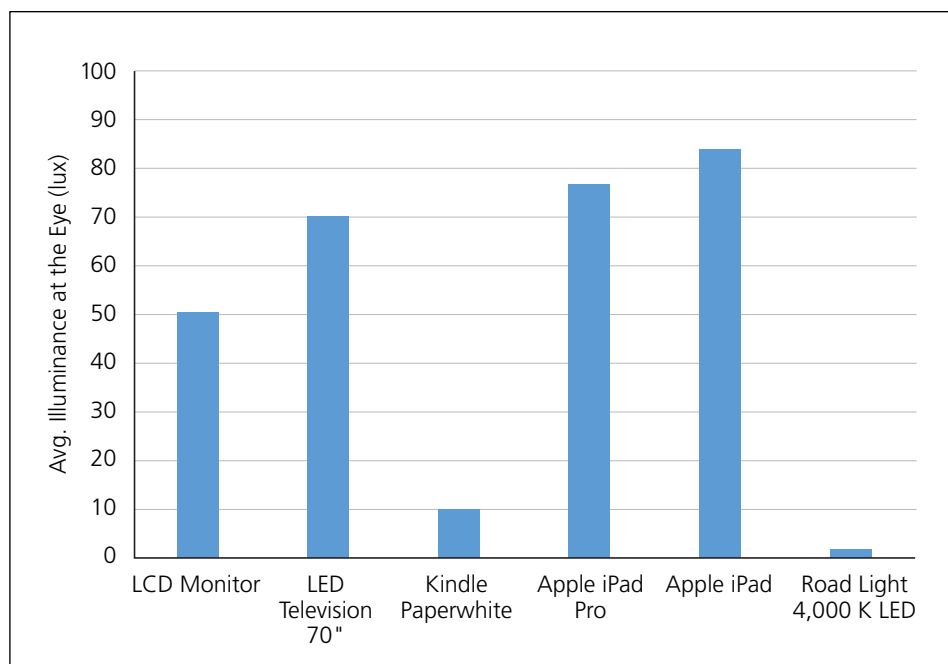


FIGURE 2 Illuminance dosage from consumer electronic devices compared to 4,000 K LED roadway lighting when the consumer devices were in full brightness mode.

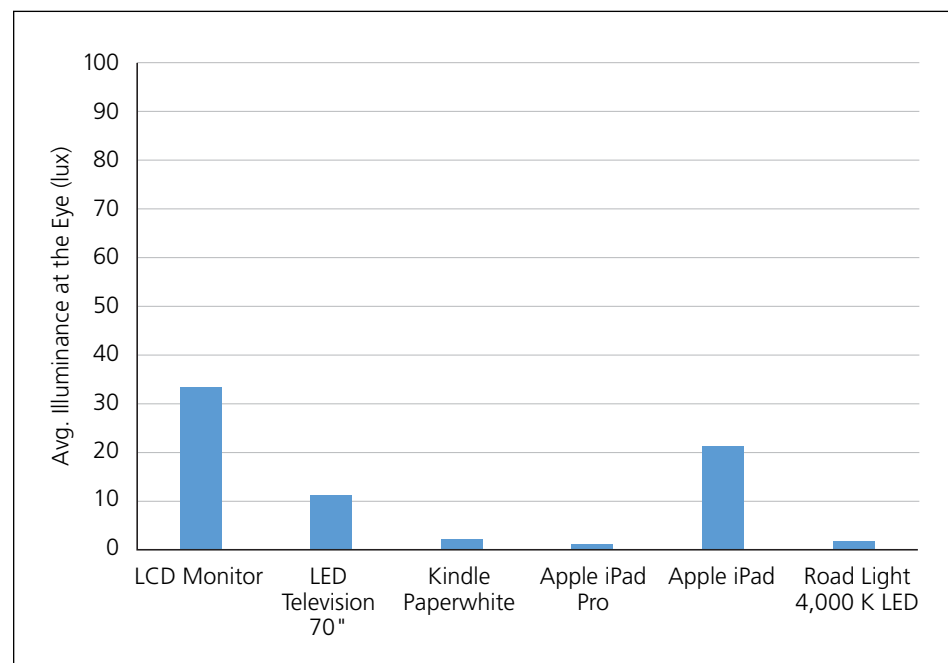


FIGURE 3 Illuminance dosage from consumer electronic devices compared to 4,000 K LED roadway lighting when the consumer devices were in dark/night mode.

5.7 hours, respectively. The potential for melatonin suppression from consumer electronic devices like televisions, monitors, and tablets is considerably higher than for LED roadway lighting. This is

supported by published research showing that light exposure from e-readers at 31.73 lux (6) and LED computer monitors at less than 100 lux (5) significantly suppress melatonin.

¹ Lux-s is the cumulative intensity of light on a surface for a given period of time, two hours in the case of this study.

² Lux/s is the intensity of light on a surface per each second.

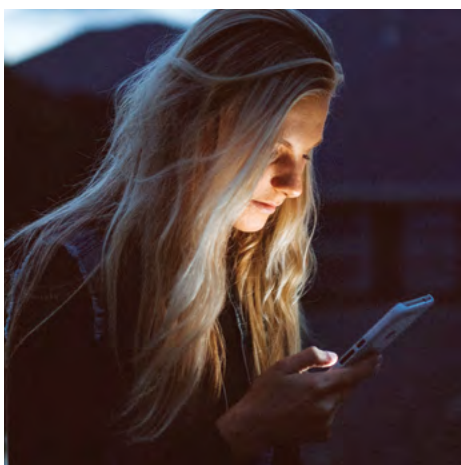


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Driver Sleep Health and Alertness Experiment

The DSHA experiment assessed the effect of an LED roadway lighting type at several illuminances on subjective and objective measures of driver sleep health and alertness. The goal was to determine the corneal illuminance that produces a measurable effect. The same objective and subjective measures of driver sleep health and alertness were measured for a positive control (only melatonin levels measured), a negative control (no roadway lighting), and a traditional HID source (a single illuminance matched to that of an LED source).

To assess driver sleep health, melatonin levels in saliva were measured. Since sufficiently bright exposure to light can suppress melatonin, melatonin levels can serve as a quantitative index related to sleep health.

Driver alertness was determined objectively by measuring reaction time, PERCLOS, and SDLP, as well as subjectively based on KSS. The DSHA experiment included 10 healthy, publically recruited male and female volunteers between ages 18 to 30. The participants were exposed to outdoor lighting environments at light levels based on recommended practice, as well as higher-than-recommended practice light levels produced on the Virginia Smart Road.

The participants drove two identically instrumented 2016 Ford Explorers equipped with data acquisition systems that collect kinematic data from the vehicle's controller area network system. Data collected included vehicle speed, differential GPS coordinates,

If that glow from your tablet or other electronic device keeps you awake at night, it may be more than the topic of your search or the conversation that causes sleeplessness. Bright light, especially within the blue range of the spectrum, can suppress the release of melatonin, a hormone that regulates sleep.

video images (e.g., driver's face, forward roadway, left side of roadway, and right side of roadway), audio from the driver, manual button presses, a lane tracker to determine vehicle position within the lane, and input from the in-vehicle experimenter.

Three roadway lighting types were evaluated (Table 1). The most common LED light source currently used for lighting roadways in the United States is the 4,000 K LED. The traditional HID roadway lighting source is the high-pressure sodium (HPS) 2,100 K HPS. These two light sources have different spectral power distributions, which allowed the researchers to assess the impacts of spectral power distribution on the objective and subjective measures of driver sleep health and alertness. The third lighting type was a no-roadway-lighting condition, which was used as a negative control.

Three light levels were identified based on the light levels that are achievable on the Virginia Smart Road and the Illuminating Engineering Society's standard specified light levels (10). A high light level of 1.5 cd/m² average luminance was selected, which is 25 percent higher than the average luminance specified for major streets with high pedestrian activity classification (1.2 cd/m²) and 50 percent higher than the average luminance specified for expressways (1.0 cd/m²). The 1.2 cd/m² measurement is the highest light

level recommended by the Illuminating Engineering Society for any kind of roadway. A medium light level of 1.0 cd/m² and a low light level of 0.7 cd/m² were selected and could be achieved across all pavement types on the Virginia Smart Road. The HPS lighting matched the highest light level of the 4,000 K LED, rather than the lowest light level.

Participants were recruited from the public to be tested under the selected experimental conditions. In the positive laboratory control, a high-intensity 4,000 K LED luminaire at close range was used to suppress the dim light melatonin onset and peak melatonin secretion. Positive control laboratory studies of nocturnal melatonin secretion served as reference points to compare the melatonin levels in the experimental driving scenarios on the Virginia Smart Road. The objective of the positive control was to strongly suppress the earlier melatonin onset and peak melatonin secretion. After completing the control testing, the realistic lighting scenarios were carried out by exposing participants to each of the test conditions while they drove on the Smart Road. During the exposures, participants' melatonin levels were quantitatively determined at 30-minute intervals. In addition to melatonin levels, participants' reaction time (measured by detection distances of objects on the roadway), PERCLOS, SDLP, and self-reported measures of drowsiness using KSS also were measured at 30-minute intervals to gauge driver alertness. Increased alertness increases driver reaction time and, in turn, lengthens the distance at which drivers can detect objects on the road. Increased PERCLOS and SDLP are associated with higher driver drowsiness.

TABLE 1 The DSHA Experiment's Independent Variables and Values

Independent Variable	Levels
Light Condition	2,100 K HPS – High (1.5 cd/m ²) 4,000 LED – High (1.5 cd/m ²) 4,000 LED – Medium (1.0 cd/m ²) 4,000 LED – Low (0.7 cd/m ²) No Roadway Lighting – (less than 0.5 cd/m ²)
Exposure Time	1 to 3 A.M. (Five saliva samples collected at 30-minute intervals)

Note:

HPS = high-pressure sodium

LED = light-emitting diode

Participants arrived at the test facility at 11 p.m., where they were exposed to 200 lux of typical indoor residential lighting for two hours. From 1 to 3 a.m., participants were exposed to the positive control or the experimental roadway lighting conditions on the Virginia Smart Road. Saliva samples were collected every 30 minutes. Between light exposures, a gap of at least one week was provided so that participants could go back to their usual sleep schedule.

Results of DSHA Experiment

The results showed that neither the 4,000 K LED roadway lighting (at high, medium, or low levels) nor the 2,100 K HPS–High lighting condition had an effect on salivary melatonin suppression (Figure 4). Numerous studies have demonstrated melatonin suppression as a result of light exposure in laboratory conditions using monochromatic light sources (4, 11–12) or broadband white sources at very high light levels of 1,000 lux and higher (13). Therefore, light exposure from any of the roadway lighting conditions—at the highest level of 1.9 lux from 4,000 K LED–High—was not strong enough to elicit a detectable salivary melatonin suppression for drivers who experienced the two-hour exposure from 1 to 3 a.m. Statistically significant differences were observed only between the positive salivary control study performed in the laboratory and all of the roadway exposure conditions. The melatonin suppression observed in the positive laboratory control study employed a bright white light (1,000 $\mu\text{W}/\text{cm}^2$; 3,500 lux) not typically encountered on roadways at night. The Illuminating Engineering Society recommends the highest street lighting of 1.2 cd/m^2 (10). Two of the tested street lighting conditions exceeded this luminance by 25 percent (1.5 cd/m^2). The highest average measured subject illuminance during exposure to the four different electrical street lighting conditions ranged from 1.1 to 1.9 lux. The average measured participant corneal illuminance during exposure to driving conditions with no roadway lighting was 1.4 lux. The current study demonstrates that the relatively dim exposures from all of the tested

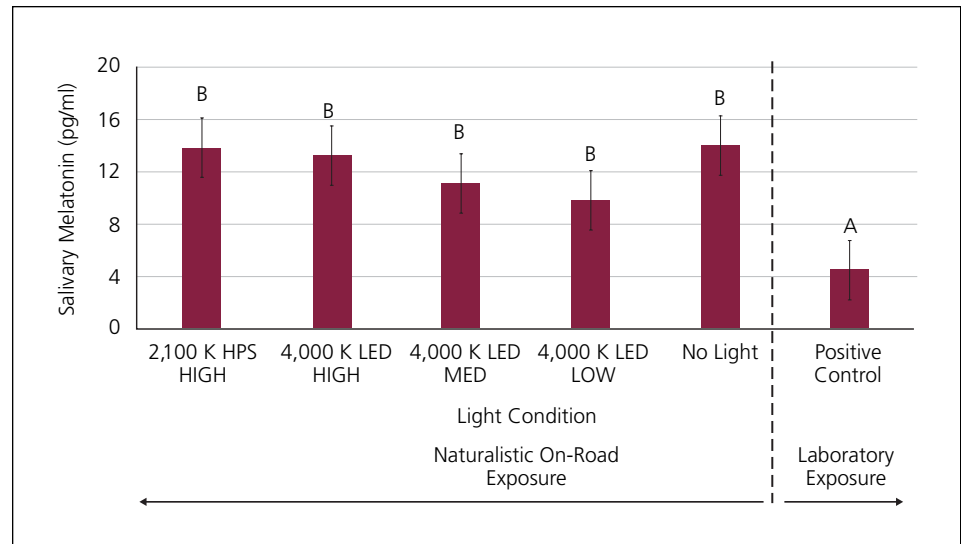


FIGURE 4 Effect of light condition on salivary melatonin. (Note: Values are least square means of melatonin. Error bars denote standard errors. Conditions with the same letters indicate no statistical differences in salivary melatonin suppression.)

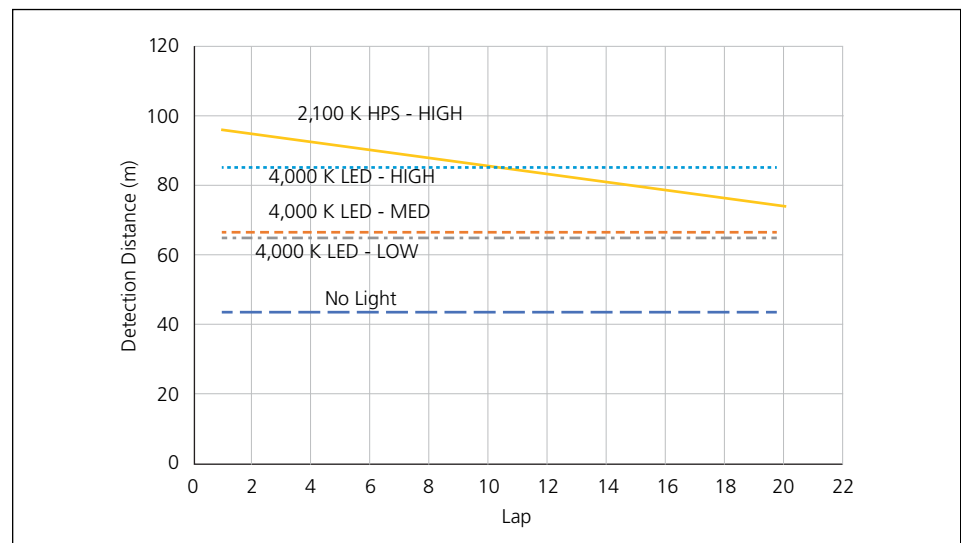


FIGURE 5 Effect of the number of roadway track laps on detection distance for each of the light conditions.

roadway lighting environments for drivers do not suppress salivary melatonin.

Increasing the light level made it easier to detect objects on the roadway from greater distances (detection distance). Under the 2,100 K HPS–High lighting condition, both detection and color recognition distances showed a decrease the longer the participants were exposed (Figure 5). Such decreases in visual performance with increase in exposure time were not observed across any of the 4,000 K LED conditions or the no-roadway-lighting condition. The decrease in detection and color recognition distance

under the 2,100 K HPS–High lighting condition could be attributed to fatigue as a result of the relative nonuniformity of the 2,100 K HPS (uniformity ratio = 7.5) over the 4,000 K LED (uniformity ratio = 4.0). A nonuniform roadway lighting condition, like 2,100 K HPS–High, has a higher number of darker and lighter bands than a more uniform roadway lighting condition, like 4,000 K LED. A longer exposure to alternating darker and brighter bands of nonuniform lighting can fatigue a driver more than uniform roadway lighting conditions. More research is required to understand if greater exposure time to the

2,100 K HPS decreases driver performance.

PERCLOS and SDLP were not affected by any of the roadway lighting conditions. With respect to PERCLOS, on average the participants' eyes were closed approximately 30 percent of the time for all roadway lighting conditions and times. This shows that in all of the roadway lighting conditions—including no roadway lighting—participants exceeded the 12 percent eye closure threshold that is associated with moderate or greater drowsiness based on existing research (14–16). This result shows that under all exposure conditions, participants were equally drowsy. There were no statistical differences in the KSS scores of any of the road lighting conditions from 1.1 to 1.9 lux, and the no-roadway-lighting condition at 0.8 lux. KSS scores in the road conditions were higher than in the positive control. This indicates that, no matter what the light level, drivers were sleepier in the road exposure conditions than in the positive laboratory control. These results show that neither the spectral power distribution of the light source nor the light level in the roadway lighting conditions significantly affected objective and subjective measures of driver alertness.

Conclusions

Overall, the study results show that LED roadway lighting does not significantly affect driver salivary melatonin and subjective and objective alertness from 1 to 3 a.m. Although the results indicated a decrease in visual performance for the 2,100 K HPS light source, those results were not confirmed by other objective measures (such as PERCLOS and SDLP) or subjective measures of alertness like KSS scores. Major differences in melatonin suppression and subjective alertness were observed between the positive laboratory control and all of the roadway lighting conditions. Also, no meaningful inferences could be made on the effects of gender on melatonin suppression or measures of alertness. These results show that illuminance dosages that affect salivary melatonin and subjective and objective alertness are much higher than those experienced on typical roadway lighted environments.

The application of roadway lighting needs should be considered in terms of several different aspects affecting the road user and the built environment. These different aspects of the roadway lighting system include safety, energy conservation, road-user acceptance, impact on user health, sky glow and light trespass, and impact on the surrounding ecology. This project primarily considered the impact on user health, roadway safety (using visual performance as a surrogate), and alertness. The results show that the spectral content and the intensity of the roadway lighting do not affect salivary melatonin suppression or alertness in the human participants. As a result, spectral power distribution of the light source is not likely to influence the health of roadway users, particularly drivers. The light dosage on the roadway is too low to elicit a measurable effect. However, the other consideration of roadway lighting spectrum and intensity is its effect on flora and fauna at or near the roadway, and these considerations need to be included in any recommendations (17–19). Future research on the use of adaptive lighting techniques—the lighting system dims or brightens in reaction to the needs of roadway users—is needed to determine how much additional energy savings this technique provides and if it reduces the negative impact of the lighting spectrum and its intensity on the surrounding ecology.

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