Assessment of photobiological safety of passing beam and driving beam headlamps with different light sources

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Abstract. The article presents the results of the research on the assessment of photobiological hazards caused by ultraviolet radiation and blue light emitted from low and high-beam headlamps with three different light sources: halogen bulb, xenon-arc and light emitting diodes (LED). The studies show that modern light sources used in automotive industry can be the cause of blue light retinal hazard. Tested headlamps with LED and xenon-arc sources are assigned to RG2 risk group according to PN-EN 62471:2010, maximum exposure times are in range of 24-40 s and threshold distances 5.3-8.3 m. There are no ultraviolet radiation hazard caused by low and high beam headlamps except for xenon lamp. Obtained results were referred to photometric and colorimetric quantities of tested headlamps.

1. Introduction
Vision is not the only phenomenon in human body caused by visible radiation. The quality and quantity of perceived light strongly affect human health and well-being. Light with certain parameters increase alertness, sleep efficiency and is used for seasonal affective disorder treatment \cite{1,2}. Visible radiation with wavelength between 400 nm and 550 nm has a strong influence on circadian system as a result of light absorption by melanopsin \cite{2,3,4}. The health effects of the circadian rhythm disturbance are currently unknown \cite{4}. Light flickering, also invisible, can cause headaches and different kinds of neurological and physiological effects \cite{2,5}. This effect is intentionally used in the automotive industry for rear car lamps dimming using PWM.

Invisible electromagnetic radiation can cause number of negative photobiological effects in human body \cite{6,7}:

\begin{itemize}
  \item cataracts caused by infrared or ultraviolet radiation;
  \item keratoconjunctivitis and erythema of the skin caused by ultraviolet radiation;
  \item thermal damage of the retina and other.
\end{itemize}

Guidelines for the photobiological safety assessment of lighting devices for radiation wavelength from 200 nm to 3000 nm are included in the EN 62471. This standard refers to five types of threats \cite{7}:

1. dermal and eye hazards caused by actinic UV radiation (wavelength $\lambda$ from 200 nm to 400 nm);
2. UV-A eye hazard ($\lambda$ from 315 nm to 400 nm);
3. blue light eye hazard ($\lambda$ from 300 to 700 nm);
4. infrared eye hazard ($\lambda$ from 780 to 3000 nm);
5. thermal hazards of the skin ($\lambda$ from 380 to 3000 nm).
The aforesaid photobiological hazards for the eye may occur during exposure to radiation sources with high energetic luminance in the range of the active spectrum of a given threat. Currently, the following eye injuries from light sources have been observed [2,7]:

- retinal damage by blue light emitted from welding arcs, ophthalmologic instruments and sun,
- eye lens and cornea diseases by ultraviolet radiation from arc light sources.

Passing beam and driving beam headlamps used in automotive industry are characterized by narrow luminous intensity distributions and light emitted from small, often uncovered light sources with luminance level up to $10^8$ cd/m$^2$. Many of them uses LED, xenon or halogen light sources. A significant part of LEDs emitting white light uses phosphors for this purpose. Such light sources are characterized by a spectral distribution with a narrow peak in the wavelength range from about 400 nm to 500 nm and wider for longer wavelengths. LED luminaires used for general lighting are often characterized by relatively large dimensions and low luminances which in most cases are assigned to exempt (RG0) and low risk group (RG1) [8,9]. Headlamps with tiny optical elements and luminous intensities more than 50 000 cd may cause higher blue light hazard. Xenon arc lamps are both a source of blue light and ultraviolet radiation. If this type of light sources does not have UV-filter, they can cause blue light and ultraviolet radiation hazard. These hazards may also apply to headlamps with halogen light sources, although emission of blue light and ultraviolet radiation is much smaller than from xenon sources. This article covers the research on the assessment of photobiological safety of headlamps with halogen, xenon-arc and LED light sources for wavelength range 200-700 nm.

2. Physical parameters for blue light and UV radiation hazard assessment

EN 62471 identifies four risk groups of photobiological hazards by lighting devices [7]:

- exempt risk group – RG0,
- low risk group – RG1,
- moderate risk group – RG2,
- high risk group – RG3.

Assessment of photobiological safety is based on irradiances or radiances for a given threat described below.

2.1. Skin and eye hazards caused by actinic UV radiation (wavelength range: 200-400 nm)

Effective irradiance for actinic UV is given by formula [7]:

$$E_S = \int_{200}^{400} E_\lambda(\lambda) \cdot S(\lambda) d\lambda$$

where:

- $E_\lambda(\lambda)$ – monochromatic irradiance in W/m$^2$/nm,
- $S(\lambda)$ – actinic UV hazard efficiency function (figure 1).

2.2. UV-A eye hazard (wavelength range: 315-400 nm)

UV-A effective irradiance is defined by [7]:

$$E_{\text{UV-A}} = \int_{315}^{400} E_\lambda(\lambda) d\lambda.$$  

For UV radiation hazard assessment, monochromatic irradiance measurements are performed at measurement distance 200 mm with aperture limiting the detector’s viewing angle to 80°.

2.3. Blue light eye hazard (wavelength range: 300-700 nm)

Depending on the size of light source, EN 62471 standard gives two possible approaches [7]:

- For light sources with light emitting surface with diameter greater than 2.2 mm using blue light hazard radiance:

$$L_B = \int_{300}^{700} L_\lambda(\lambda) \cdot B(\lambda) d\lambda$$

where:

- $L_\lambda(\lambda)$ – monochromatic radiance in W/(m$^2$ sr nm),
\( B(\lambda) \) – blue light hazard efficiency function (figure 1).

Blue light radiance can be calculated from luminance [10]:

\[
L_B = K_{B,V} \cdot L
\]

(4)

where \( K_{B,V} \) is the blue light efficacy of luminous radiation [10]:

\[
K_{B,V} = \frac{\int_{380}^{700} \phi_\lambda(\lambda) \cdot B(\lambda) d\lambda}{K_m \int_{380}^{700} \phi_\lambda(\lambda) V(\lambda) d\lambda} = \frac{L_B}{L} = \frac{E_B}{E}
\]

(5)

where:

\( \phi_\lambda(\lambda) \) – monochromatic radiance \( L_\lambda(\lambda) \) in \( \text{W/(sr} \cdot \text{m}^2 \cdot \text{nm}) \) or monochromatic irradiance \( E_\lambda(\lambda) \) in \( \text{W/m}^2 \)/nm,

\( V(\lambda) \) – relative spectral responsivity of the human eye (figure 1),

\( K_m = 683 \text{ lm/W} \).

- For light sources witch diameter smaller than 2.2 mm using blue light hazard irradiance:

\[
E_B = \int_{380}^{700} E_\lambda(\lambda) \cdot B(\lambda) d\lambda.
\]

(6)

where \( E_\lambda \) is monochromatic irradiance in \( \text{W/m}^2 \)/nm.

For blue light hazard assessment, monochromatic irradiance or radiance measurement is performed with aperture limiting the detector’s viewing angle to 11 mrad..

**Figure 1.** UV, blue light hazard efficiency function and relative spectral responsivity of human eye

Exposure limits for blue light and ultraviolet photobiological hazard assessment are shown in table 1.

**Table 1.** Exposure limits for risk groups [7]

| Hazard                  | Designation | Risk group | Units                |
|-------------------------|-------------|------------|----------------------|
|                         |             | RG0        | RG1         | RG2         |                      |
| Actinic UV              | \( E_S \)   | 0.001      | 0.003      | 0.03        | \text{W/m}^2        |
| UV-A                    | \( E_{UVA} \)| 10         | 33         | 100         | \text{W/m}^2        |
| Blue light              | \( L_B \)   | 100        | 10000      | 4\times10^6  | \text{W/m}^2 \cdot \text{sr}^{-1} |
| Blue light - small sources | \( E_B \)   | 1          | 1          | 400         | \text{W/m}^2        |
3. Measurement result
The photobiological safety assessment was carried out for both low and high beam headlamps with three different light sources:
- halogen bulb,
- LED,
- xenon-arc.
Relative spectral distributions are compared on figure 2.

![Figure 2. Relative spectral distributions of halogen, LED and xenon light sources of tested headlamps](image)

For further analysis correlated colour temperature ($CCT$), chromaticity coordinates ($x,y$), maximum luminance in the field of view 11 mrad and illuminance are shown.

All measurements have been performed in the direction of maximum irradiance at a distance 200 mm from photometric centre. A wide-band spectroradiometer was used for this purpose. For blue light hazard assessment imaging luminance measurement device was used.

| Parameter | Units | low beam | high beam |
|-----------|-------|----------|-----------|
|           |       | halogen  | LED       | xenon     |
|           |       | halogen  | LED       | xenon     |
|           |       | halogen  | LED       | xenon     |
| $CCT$     | K     | 3100     | 7100      | 4100      |
| $x$       | -     | 0.425    | 0.304     | 0.369     | 0.425     | 0.304     | 0.369     |
| $y$       | -     | 0.396    | 0.307     | 0.357     | 0.396     | 0.307     | 0.357     |
| $E$       | lx    | 5.72·10$^4$ | 8.73·10$^4$ | 8.21·10$^4$ | 4.54·10$^4$ | 1.12·10$^5$ | 2.67·10$^5$ |
| $L$       | cd·m$^{-2}$ | 1.56·10$^7$ | 2.63·10$^7$ | 4.47·10$^7$ | 1.83·10$^7$ | 3.53·10$^7$ | 5.89·10$^7$ |
| $E_UVA$   | W·m$^{-2}$ | 6.7·10$^5$ | 2.6·10$^5$ | 1.5·10$^4$ | 5.7·10$^5$ | 3.4·10$^5$ | 5.0·10$^4$ |
| $E_{UV}$  | W·m$^{-2}$ | 5.6·10$^{-1}$ | 5.2·10$^{-1}$ | 4.4·10$^{0}$ | 4.5·10$^{-1}$ | 6.7·10$^{-1}$ | 1.4·10$^{1}$ |
| $L_B$     | W·m$^{-2}$·sr$^{-1}$ | 5.7·10$^3$ | 2.5·10$^4$ | 3.2·10$^4$ | 6.7·10$^3$ | 3.4·10$^4$ | 4.2·10$^4$ |
Headlamps hazard assessment based on proper radiometric quantities for UV and blue light hazards are presented in table 3.

**Table 3. Photobiological hazards assessment according to PN-EN 62471:2010**

| Hazard Parameter | Units | low beam | high beam |
|------------------|-------|----------|-----------|
| Actinic UV $E_s$ | W·m$^{-2}$ | 6.7·10$^{-5}$ | 2.6·10$^{-5}$ | 1.5·10$^{-4}$ | 5.7·10$^{-5}$ | 3.4·10$^{-5}$ | 5.0·10$^{-4}$ |
| risk group       | -     | RG0      | RG0       | RG0       | RG0       | RG0       |
| UV-A $E_{UVA}$   | W·m$^{-2}$ | 5.6·10$^{-1}$ | 5.2·10$^{-1}$ | 4.4·10$^{0}$ | 4.5·10$^{-1}$ | 6.7·10$^{-1}$ | 1.4·10$^{1}$ |
| risk group       | -     | RG0      | RG0       | RG0       | RG0       | RG0       |
| Blue light $L_B$ | W·m$^{-2}$·sr$^{-1}$ | 5.7·10$^{3}$ | 2.5·10$^{4}$ | 3.2·10$^{4}$ | 6.7·10$^{3}$ | 3.4·10$^{4}$ | 4.2·10$^{4}$ |
| risk group       | -     | RG1      | RG2       | RG2       | RG1       | RG2       |
| Overall photobiological hazard assessment | - | RG1 | RG2 | RG2 |

For all types of headlamps blue light hazard may occur. Therefore, the maximum exposure times for blue light hazard have been calculated (table 4) using formula [7,10]:

$$t_{B,max} = \frac{I_{B,max}}{L_B} [s].$$  \hspace{1cm} (7)

According to IEC TR 62778 recommendations, calculations of the threshold distance for lighting devices classified to moderate risk group (RG2) for blue light hazard have been made – table 4. Threshold distance is the distance where maximum exposure time is equal to 100 s. Therefore $E_B$ is equal 1 W·m$^{-2}$ for viewing angle smaller than 11 mrad. This distance is given by [10]

$$d_{thr} = \sqrt{\frac{I_{max}}{E_{thr}}} [m],$$  \hspace{1cm} (8)

where $I_{max}$ is the maximum luminous intensity of low or high beam and

$$E_{thr} = \frac{1}{\kappa_{B,Y}} [lx].$$  \hspace{1cm} (9)

**Table 4. Maximum exposure times, maximum intensities on threshold distances of tested lights**

| Parameter | Units | low beam | high beam |
|-----------|-------|----------|-----------|
| $t_{B,max}$ | s | 175 | 30 | 31 | 150 | 40 | 24 |
| $I_{max}$ | cd | - | 29900 | 67000 | - | 50400 | 95600 |
| $d_{thr}$ | m | - | 5.3 | 6.9 | - | 6.9 | 8.3 |

Also for xenon high beam near-UV hazard may occur. Maximum exposure time for UV-A hazard is given by:

$$t_{UVA,max} = \frac{10^4}{E_{UV A}} [s].$$  \hspace{1cm} (10)
Therefore, maximum exposure time for xenon high beam is equal to 714 s.

4. Conclusions
The studies show that modern light sources used in automotive industry can be the cause of blue light retinal hazard. This problem applies to much lesser extent to headlamps with halogen light sources that have been classified to low risk group. There are no ultraviolet radiation hazard caused by low and high-beam headlamps except for xenon high beam which was assigned to low risk group for UV-A radiation hazard. The maximum exposure time for this source is equal 714 s. However, requirements for ultraviolet radiation emission of lighting devices used in automotive industry are included in Regulation No. 37 ECU UN for halogen lamps and Regulation No. 99 ECE UN for gas-discharge lamp sources. These requirements were also met by tested headlamps with halogen and xenon light sources, what was investigated.

The maximum exposure times for blue light hazard are relatively short for LED and xenon headlamps – table 4. They are comparable with exposure times from welding arcs that are in the range of 0.47-34 s [11,12]. An even greater hazard may be caused by xenon-arc lamps with higher correlated colour temperature which should be investigated. These light sources with CCT’s up to 12 000 K are currently available on the automotive market and can be easy replaced by car users in their headlamps. For xenon-arc headlamps which such CCT’s UV-A hazard may also occur at small distances.

According to table 4, estimated threshold distances for blue light hazard are greater than 5.3 m. For smaller distances maximum exposure times will decrease.

The potential hazard situations may occur during car repair works at small distances from headlamps or with long exposure to light from badly set or oriented headlamps.

Nowadays, the luminance of currently used LED sources is growing rapidly and is comparable with xenon-arc light sources (table 2). Since blue light hazard increases linearly with luminance, the ongoing photobiological safety assessment of lighting devices with LED light sources proves to be necessary.

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