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Assessment of the visibility of unprotected road users in pedestrian crossing

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Abstract: The article presents selected results of research on improving pedestrian traffic safety. Based on annually-updated accident statistics made available by the police, as well as the new pedestrian traffic regulations in force, detailed work was undertaken to assess the level of visibility of pedestrians by drivers in pedestrian crossing areas. The research was carried out by analyzing several characteristic cases of pedestrian crossings occurring in Poland, in which there was only dedicated lighting for crossings, only street lighting, and a variant of coexistence of both of the above lighting solutions. Illuminance measurements were made in the horizontal and vertical planes of pedestrian crossings, and the results were confronted with the relevant guidelines. The next step involved a complementary measurement of the luminance distribution of the vertical plane containing the pedestrian and a portion of the sub- and super-horizontal background. Visibility pedestrians was considered in positive and negative contrast variants, and was then related to the obtained results of the illumination distribution. The analysis of the results of the study indicated the possibility of limited visibility of pedestrians at the crossings despite the satisfactory results obtained from measurements of the illuminance distribution within the crossings.

Key words: luminance distribution, pedestrian crossings, pedestrian visibility, road lighting, traffic safety



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1. Introduction

The ability of drivers to quickly notice pedestrians moving through pedestrian crossings depends on a number of factors. The key ones include the time of day (day, night), the visibility of the object of visual processing against the background caused by the contrast of luminance, color or both at the same time, the speed of the vehicle and pedestrian, the angular size of the detail of visual processing, and the individual characteristics of the visual apparatus (age-dependent adaptive features of vision) [1–5].

For the purposes of the planned research work, the focus was on the evening and night time, when risk of loss of health or life for vulnerable road users using pedestrian crossings is statistically the highest [6, 7].

Currently in Poland, as well as in Europe, there are no uniform requirements for pedestrian crossing lighting. EN 13201 provides general guidelines for the lighting of the listed areas [8]. In 2018, in Poland, the Ministry of Infrastructure published “Guidelines for the organization of safe pedestrian traffic – guidelines for proper lighting of pedestrian crossings”, which defines a PC lighting class dedicated to pedestrian crossings [9]. This class is directly related to the lighting class of the roadway and includes requirements for horizontal and vertical illuminance values in the pedestrian crossing area. Currently, the listed requirements are the most commonly used in the design and modernization of pedestrian crossing lighting in Poland.

To reduce the magnitude of incidents at pedestrian crossings involving vulnerable road users, among the elements already mentioned, the luminance contrast between the object (the pedestrian’s apparent surface visible as a secondary light emitter) and the background is also crucial. This contrast can be achieved by varying the luminance of the background and the object (positive or negative contrast) [10, 11]. Referring to current statistical research published in the scientific literature on the subject, it should be noted that during the autumn-winter-spring period, dark colors of clothing are definitely dominant among pedestrians, and this directly affects the difficulty of obtaining positive contrast in the conventional vertical plane of pedestrian crossings [12].

Pedestrian visibility at night, mainly by motorized road users, is an important area of research related to the safety of unprotected road users. Article [13] presents research results on the perception distance of a pedestrian illuminated by car low beam headlights. The research was carried out for two cases: a pedestrian without a reflective element and then equipped with a reflective band placed on the forearm. The research results confirmed that the use of a reflective element significantly reduces the risk of a road accident involving a pedestrian, increasing threefold the distance (from 27 m to 81 m) from which a pedestrian is visible to the driver of a motor vehicle.

In the case of pedestrian crossing areas where the paths of vulnerable road users and motor vehicles intersect, the lighting produced only by the vehicle’s lights is insufficient, and the best lighting conditions in these zones are provided by the use of lighting luminaires in the crossing area. Research has been carried out in world literature on the value of lighting intensity ensuring sufficient visibility of pedestrians. In publications [14, 15], the authors indicated 40 lx as the value of vertical illumination enabling proper visibility of pedestrians. The research carried out by Gibbons and Hankley [16] showed that 20 lx is a value ensuring a sufficient level of perception of objects in the area of pedestrian crossings.

Article [17] analyzed the impact of the number of lanes, nearby vegetation and the color temperature of lighting on pedestrians when crossing a pedestrian crossing. The obtained results showed an improvement in safety related to the reduction of the number of traffic lanes and the use of a lighting color temperature of 4 500 K.

General thoughts on the lighting of pedestrian crossings related to the pedestrian's clothing, the contrast of the pedestrian's luminance and his background, and the complementation of street lighting with the lighting dedicated to crossings are presented in publication [18].

Research on pedestrian visibility and the obtained luminance contrast using luminaires with different light source technologies is presented in article [19]. Among the analyzed light sources (metal halide, induction and LED), the highest uniformity of illumination and the obtained pedestrian contrast were demonstrated for the metal halide source.

Another area of research related to lighting, including pedestrian crossings, is not directly related to the visibility of pedestrians in the crossing zone but related to the energy efficiency of the lighting installation. Articles [20–22] present research results related to the optimization of lighting installations and the use of intelligent systems enabling an increase in the energy efficiency of the installation, which reduces CO₂ emissions.

Research results in the area related to intelligent pedestrian detection systems within pedestrian crossings are also published [23–25]. They describe the basic advantages as well as limitations regarding the use of image systems for pedestrian detection. Due to the low value of illumination and its low uniformity, the quality of image generation is low, which seriously affects the efficiency of the mentioned technology. Another solution for pedestrian detection is the use of thermal images based on the difference in thermal radiation of an object without the influence of the quality of external light [26, 27].

The presented research results lack considerations regarding the impact of the layout geometry and lighting technology in creating pedestrian visibility within a pedestrian crossing. Does the installation of road lighting within the crossing enable the expected parameters to be achieved or is it necessary to install dedicated lighting or the coexistence of both solutions? The above-mentioned issue is particularly important in the context of the latest requirements for the lighting of pedestrian crossings in Poland [9].

This raises the question of to what extent the system of primary light emitters, installed within the pedestrian crossing, affects the achievement of the expected luminance contrast between the pedestrian and the background. Of course, lighting systems affecting the pedestrian crossing area can be configured from among the technically available variants, i.e., only street lighting (single-sided or double-sided), dedicated lighting for pedestrian crossings (the classic variant of luminaires mounted above the pedestrian crossing as well as modern solutions of luminaires installed in front of the pedestrian crossing with asymmetrical distribution) and a combination of the two previous solutions.

It would be expected that luminaires dedicated to illuminating pedestrian crossings would direct light into the pedestrian crossing area in such a way as to provide the recommended values of illuminance distribution at the designated points of the measured horizontal and vertical plane [6]. In addition, it would be imperative to check whether the rays of light reflected from the ground, the surroundings and the pedestrian would create favorable conditions to produce a luminance contrast of the value expected for good visibility of pedestrians. Slightly different is the situation in which there is only road or street lighting in the pedestrian crossing area (there are many such cases in Poland). This raises the question of whether, even for the specific case of a road lighting pole positioned directly adjacent to a pedestrian crossing, lighting conditions will be sufficiently favorable to produce the expected luminance contrast between the background and the pedestrian.

2. Adopted research methodology

Four pedestrian crossings with varying technology, aiming and placement of luminaires illuminating pedestrian crossing waiting areas as well as the crossing themselves were selected for detailed studies. The first of the pedestrian crossings considered represents the case of illuminating the pedestrian crossing with only street sodium-vapor luminaires (Fig. 1), the next pedestrian crossing was illuminated with a dedicated luminaire and supplementary street sodium-vapor luminaires (Fig. 2), the next variant was illuminated only with a D6 information sign (Fig. 3) and the last crossing was illuminated with LED street luminaires and, in addition, a dedicated LED luminaire with asymmetrical light distribution (Fig. 4). For the studied pedestrian crossings, horizontal and vertical illuminance measurements were carried out with respect to the assigned PC class [6]. Illuminance measurements were made using Konica Minolta T10-A illuminance meter [28]. The next stage involved determining the visibility of the pedestrian at the studied pedestrian crossing. For this purpose, luminance measurements of the pedestrian and the background were taken, based on which luminance contrast was determined [29]. The measurements were carried out for two variants of the upper part of pedestrian clothing (sweatshirt): for its light color with a reflectance of $\rho = 0.78$ and for a dark color with a reflectance of $\rho = 0.08$. For the two colors of the upper part of the clothing, the pedestrian contrast was determined in accordance with Fig. 6. Measurements were made using the LMK mobile air matrix luminance meter [30, 31].



Fig. 1. Daytime view of pedestrian crossing no. 1 without dedicated lighting located on a two-way single-lane street with street lighting located only on one side (a) and nighttime visibility of a pedestrian in light-colored clothing waiting to cross the street (b)

The first of the selected pedestrian crossings was located on a two-way, single-lane street. The pedestrian crossing was lit only by street lighting luminaires installed in a one-sided arrangement. Based on the documentation provided by the road manager and our own luminance tests, the road lighting class was determined as M4 and the corresponding pedestrian crossing lighting class as PC3 (Table 1) [9].

Another studied crossing was located on a three-lane two-way road. The pedestrian crossing is illuminated with street 150 W OUS sodium-vapor luminaires. Luminaires installed at a height of 10 m in an alternating pattern, one of the street luminaires installed at a distance of 2 m from the pedestrian crossing. In this case, the aisle was additionally illuminated by a single Calypso

Zebra dedicated 150 W gas-discharge luminaire. The lighting class of the roadway was M4, and the lighting class of the pedestrian crossing was PC3 (Table 1) [9]. Figure 2 shows a daytime view of the second studied pedestrian crossing and a nighttime view of the pedestrian in the waiting area of the crossing.

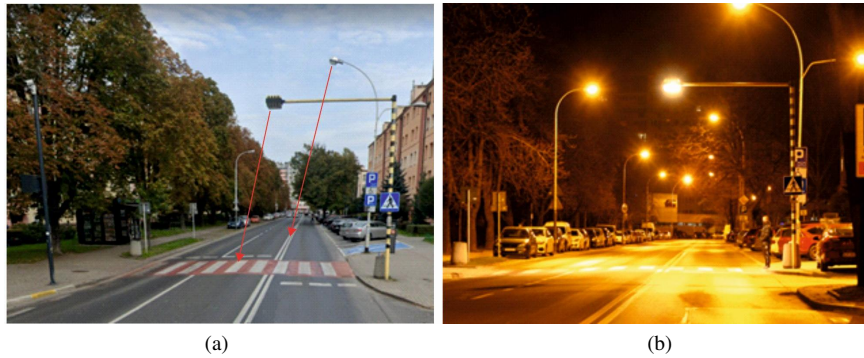


Fig. 2. Daytime view of pedestrian crossing no. 2 with dedicated pedestrian crossing lighting on a two-way street with street lighting on both sides (a) and visibility of a pedestrian in dark-colored clothing waiting to cross the street (b)



Fig. 3. Daytime view of pedestrian crossing no. 3 with dedicated pedestrian crossing lighting on a single-lane two-way street with a separator lane without additional street lighting (a) and visibility of a pedestrian in dark-colored clothing waiting to cross the street (b)

The third variant was located on a two-lane two-way road. The illumination of the pedestrian crossing is achieved by a standalone lighting system centrally located above the crossing with an LED source and an additionally illuminated D-6 sign. There are no street luminaires within the pedestrian crossing. The lighting class of the roadway is M4, and the lighting class of the pedestrian crossing is PC3 (Table 1) [9].

The final studied pedestrian crossing example was located on a two-way road with three lanes in direction 1 and two in direction 2. Two luminaires for street lighting are located near the pedestrian crossing area, and in addition, two luminaires dedicated to lighting pedestrian crossings with asymmetrical light distribution are used. All of the luminaires mentioned above use solid-state light sources. The lighting class of the roadway is M4, and the lighting class of the pedestrian crossing is PC3 (Table 1) [9].



Fig. 4. Daytime view of pedestrian crossing no. 4 with dedicated pedestrian crossing lighting on a sectional two-lane and three-lane two-way street with street lighting on both sides (a) and the visibility of a pedestrian in light-colored clothing waiting to cross the street (b)

Table 1. Required parameter levels of illuminance at pedestrian crossings and uniformity of illumination using asymmetrical distribution luminaires/dedicated lighting for roadways with M class illumination (luminance) [9]

Road lighting		Pedestrian crossing lighting					
		PC – class level	Measuring planes				Points A, B, C, D, E, F
Values before and after the pedestrian crossing	Vertical		Horizontal		$E_{V\ MIN(A, B, \dots)}$		
	$E_{V\ AV}$		$U_{0\ V}$	$E_{H\ AV}$		$U_{0\ H}$	
M-class level	L_{AV} [cd/m ²] (operating minimum)	[lx] (operating minimum)	[-] (min)	[lx] (operating minimum)	[-] (min)	[lx] (operating minimum)	
M1	2.00	No need to use dedicated solutions					
M2	1.50	PC1	75	0.35	75	0.35	5.0
M3	1.00	PC2	50	0.35	50	0.35	4.0
M4	0.75	PC3	35	0.35	35	0.35	4.0
M5	0.50	PC4	25	0.35	25	0.35	3.0
M6	0.30	PC5	15	0.35	15	0.35	2.0

Lighting measurements of the selected pedestrian crossings were divided into two stages. The first involved recording illuminance at designated points in the studied areas, and the second involved measuring luminance contrast in the waiting and crossing areas, for the adopted pedestrian clothing colors. The illuminance distribution measurements made it possible to assess the level of illumination of the crossing and waiting areas, achieved only by dedicated pedestrian crossing luminaires, street luminaires or a combination of both. The work also made it possible to relate

the results to the latest guidelines for lighting pedestrian crossings [9]. It was necessary in this regard to measure the lighting conditions of the pedestrian crossing and waiting areas in two perpendicular planes of measurement (Fig. 5).

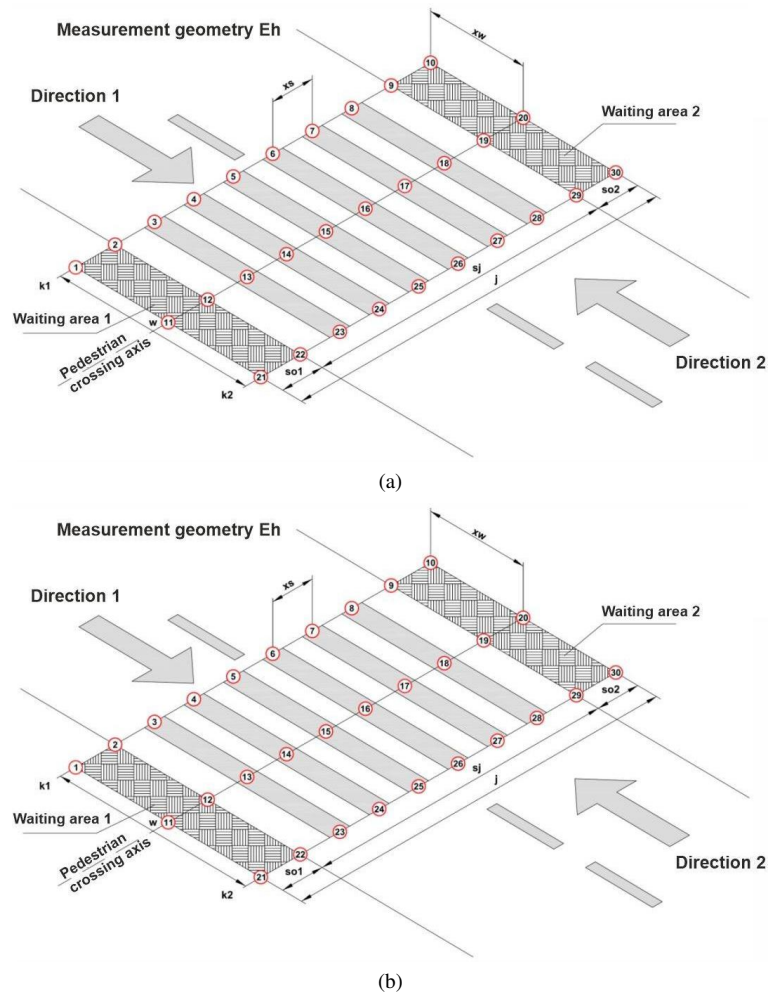


Fig. 5. Diagram of the pedestrian crossing illumination measuring point grid: in the horizontal plane (a); in the vertical plane (b) [9]

Taking into account the appropriate M lighting class levels selected for each roadway and the resulting selection of PC class levels for pedestrian crossings, normative guidelines for minimum values of average illuminance in the vertical and horizontal planes ($E_{V\text{AV}}$, $E_{H\text{AV}}$) and illuminance uniformity (U_{OV} , U_{OH}) were obtained. These values were compared to the measurement results for each roadway, assessing the possibility of providing the required lighting conditions for the pedestrian crossing in accordance with the guidelines, not only through the use of dedicated luminaires but, under favorable conditions for the location of lighting poles, also through street luminaires.

The second stage of the research included work related to luminance measurements and, more specifically, luminance contrast measurements. Measurements were carried out for two cases of pedestrian clothing in light and dark colors, in the waiting area and in the middle of the traffic lane. Three measurement fields were determined on the photographs taken and processed into luminance distributions. The first determined the luminance of the pedestrian (L_O), and was located across the width of the pedestrian's lateral contour, from the knees to the neck. In the next step, the same luminance measurement fields of the background surrounding the pedestrian (L_T) were determined, tangent to the right and left of the L_O area (Fig. 6(a)).

Measurements of the luminance contrast of the object (pedestrian) and background were made using a matrix luminance meter G (Fig. 6(b)). The measurement was performed from a distance of about 60 meters of the head of the matrix luminance meter from the P measuring surfaces. The luminance meter's head was set at a height of 1.5 meters from the ground and pointed toward the center of each of the three measuring fields.

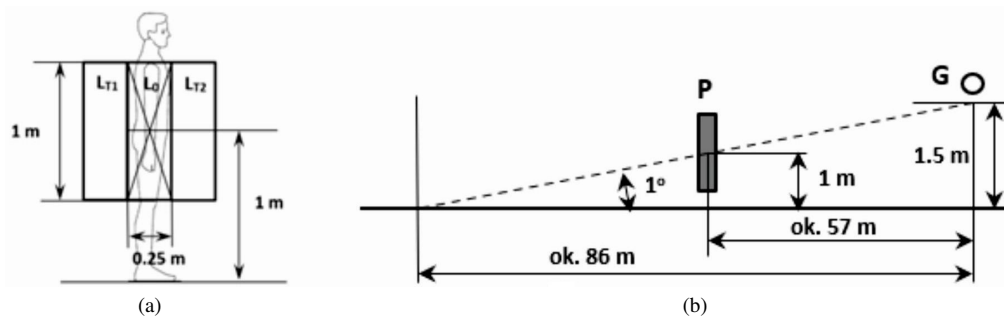


Fig. 6. Illustration showing: the method for determining the luminance fields of the L_O object and the L_T background (a); the measurement system used includes the object's luminance field and background's luminance fields (b) [10]

Assuming that the pedestrian's lateral surface (clothing) is porous, thus achieving Lambertian reflectance, and that the pedestrian's immediate background also exhibits analogous reflective characteristics, relationship (1) can be used to determine the luminance. This formula relates, under approximately homogeneous lighting conditions of a given transition area, the color characteristics of the garment, the ρ reflectance value to pedestrian's L luminance:

$$L = \frac{E \cdot \rho}{\pi}, \quad (1)$$

where: L is the luminance at the point of the illuminated surface, E is the illuminance at the point of the illuminated surface and ρ is the reflectance of the illuminated surface.

Since the background surrounding the pedestrian contour was assumed to include two surfaces on the pedestrian's right and left sides, the background luminance values had to be calculated using Formula (2):

$$L_T = (L_{T1} + L_{T2})/2, \quad (2)$$

where: L_T is the total background luminance, L_{T1} is the luminance of the first part of the background and L_{T2} is the luminance of the second part of the background.

Finally, having obtained the average luminance values of the object's surface and background, luminance contrast can be calculated, which is a light parameter directly related to the object's visibility. The luminance contrast of the object and its background was determined according to the following formula:

$$K = \frac{L_O - L_T}{L_T}, \quad (3)$$

where: K is the luminance contrast, L_O is the object luminance and L_T is the total background luminance.

From Formula (3), it is clear that the luminance contrast can take on a positive or negative value. For motorists, the most disadvantageous situation will occur when there are small differences between the luminance of the object and the background. Increased luminance contrast will promote improved pedestrian visibility at pedestrian crossings [1].

The measurements were made at night on one day, during the measurements, the conditions were dry, the ambient temperature at the beginning of the measurements was 11 and at the end of 8°C.

3. Study results

Horizontal and vertical illuminance measurements were taken for all tested pedestrian crossings. Measurement points of horizontal illuminance were located along the axis of the pedestrian crossing and two edges (k1 and k2). In accordance with the guidelines for control measurements of pedestrian crossing lighting, the measurement of lighting intensity in the vertical plane was performed for one height of 1 m along the axis of the crossing for two directions of traffic [9]. Tables 2 and 3 present the final results for all analyzed pedestrian crossings, for horizontal and vertical illuminance measurements, respectively.

The distribution of horizontal illuminance is shown in Fig. 7. The obtained value of average horizontal illuminance of 8.4 lx and in the vertical illuminance of 3.6 and 7.6 lx, respectively, is several times lower than the value required for PC3 class (35 lx). This is due to the fact that the lighting used the pedestrian crossing is street luminaires, there is no dedicated lighting, additionally located at a considerable distance from the crossing area.

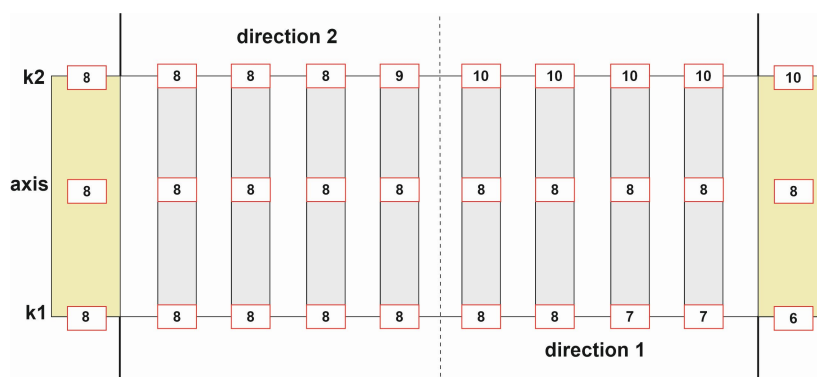


Fig. 7. Distribution of horizontal illuminance for pedestrian crossing no. 1

In addition, in order to assess the visibility of the pedestrians in the crossing area, the luminance distribution of the pedestrian and the background was measured to determine the luminance contrast. The measurement was made from a distance of 60 m for both directions of traffic and for light and dark pedestrian clothing in the waiting area and the central crossing area. The collective results of the pedestrian luminance contrast are presented in Table 4, while Fig. 8 shows the distribution of pedestrian and background luminance for crossing no. 1.

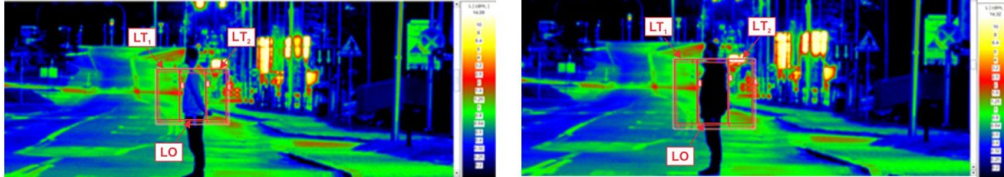


Fig. 8. Distribution of the pedestrian and background luminance for pedestrian crossing no. 1 (light and dark pedestrian clothing – direction 1)

For pedestrian crossing no. 2, analogous illuminance measurements were carried out as for crossing no. 1 and their results are summarized in Fig. 9 and Tables 2 and 3.

Table 2. Horizontal illuminance and uniformity of illumination for pedestrian crossing no. 1

Number of the pedestrian crossing	E_{HAV} [lx]	U_{0H} [-]
Pedestrian crossing no. 1	8	0.76
Pedestrian crossing no. 2	128	0.43
Pedestrian crossing no. 3	9	0.13
Pedestrian crossing no. 4	69	0.70

Table 3. Vertical illuminance and illuminance uniformity for pedestrian crossing no. 1

Number of the pedestrian crossing	Observer direction	E_{VAV} [lx]	U_{0V} [-]
Pedestrian crossing no. 1	Direction 1	4	0.61
	Direction 2	8	0.56
Pedestrian crossing no. 2	Direction 1	102	0.22
	Direction 2	42	0.34
Pedestrian crossing no. 3	Direction 1	1	0.14
	Direction 2	1	0.20
Pedestrian crossing no. 4	Direction 1	21	0.46
	Direction 2	22	0.76

Table 4. Pedestrian luminance contrast

Number of the pedestrian crossing	Observer direction	Clothing color	Center of pedestrian crossing	Waiting area
Pedestrian crossing no. 1	Direction 1	Light	0.71	2.40
		Dark	-0.64	-0.48
	Direction 2	Light	-0.40	0.10
		Dark	-0.73	-0.67
Pedestrian crossing no. 2	Direction 1	Light	3.91	5.34
		Dark	-0.47	-0.42
	Direction 2	Light	1.15	3.56
		Dark	-0.58	-0.24
Pedestrian crossing no. 3	Direction 1	Light	5.44	20.0
		Dark	-0.06	0.15
	Direction 2	Light	11.0	-0.13
		Dark	0.25	-0.63
Pedestrian crossing no. 4	Direction 1	Light	2.1	3.74
		Dark	-0.37	-0.42
	Direction 2	Light	2.1	3.29
		Dark	-0.39	-0.43

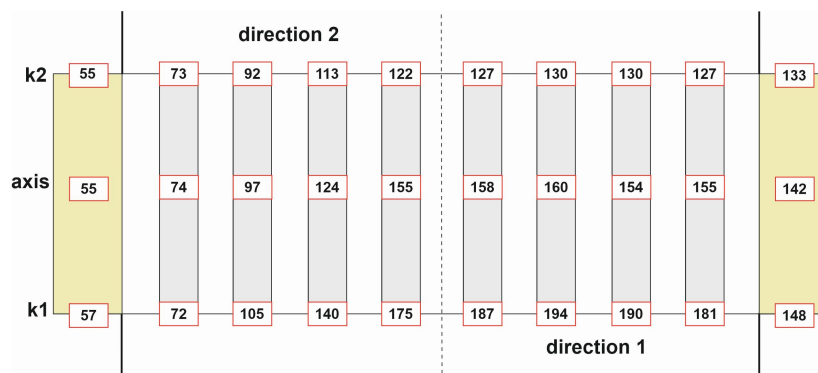


Fig. 9. Distribution of horizontal illuminance for pedestrian crossing no. 2

The horizontal and vertical illuminance results obtained were well above the required values for the PC3 class. The horizontal average illuminance value was 127.5 lx with a uniformity of 0.43, due to the location of the street luminaires in close proximity to the pedestrian crossing and the installation of a luminaire dedicated to the crossing area. The average vertical illuminance

for direction 1 was 101.6 lx, a value attributable to the installation of a dedicated luminaire with asymmetrical light distribution in line with direction 1. For direction 2, the value was 41.6 lx and was mainly attributable to the light distribution of the street luminaire. The obtained uniformity of vertical illuminance was below the required value for PC3 class (0.35), mainly for direction 2. Figure 10 shows the distribution of the pedestrian and background luminance for the analyzed pedestrian crossing. Pedestrian luminance contrast values are presented in Table 4.

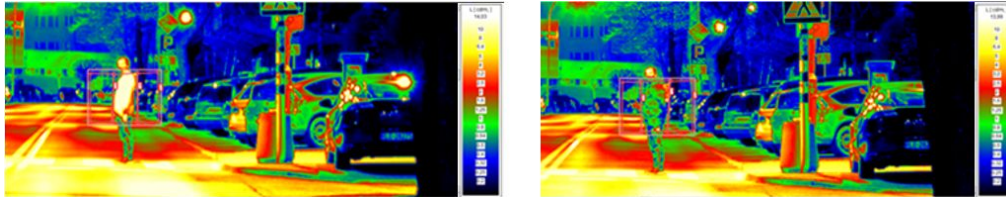


Fig. 10. Distribution of the pedestrian and background luminance for pedestrian crossing no. 2 (light and dark pedestrian clothing – direction 1)

For light pedestrian clothing, high positive contrast values were obtained, both in the middle of the pedestrian crossing and in the waiting area, with the contrast for direction 1 being about twice as high. In the case of dark pedestrian clothing, a negative contrast of similar value was obtained for both traffic directions.

The distribution of horizontal illumination intensity for the tested pedestrian crossing no. 3 is shown in Fig. 11.

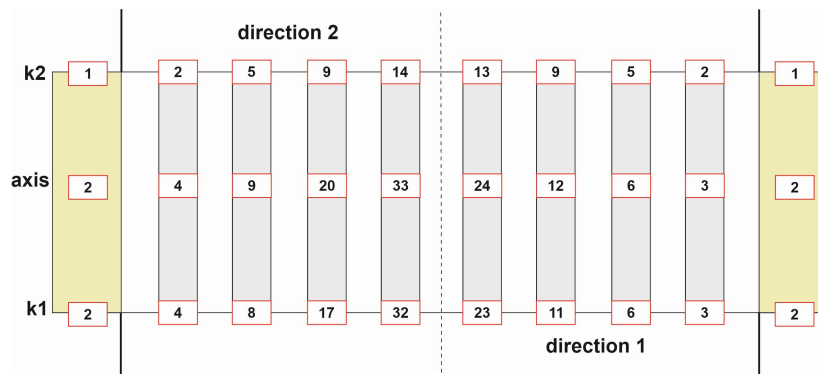


Fig. 11. Distribution of horizontal illumination for pedestrian crossing no. 3

The obtained values of horizontal and vertical illuminance were significantly lower than the requirements in the assumed lighting class for pedestrian crossings (PC3), which was due to the lighting system used. The average horizontal illuminance was 9.4 lx, with negligible values within the waiting area being of note. The lighting method used also failed to achieve the required vertical illuminance values, which averaged about 1 lx for both directions of traffic (Tables 2, 3). In contrast, Fig. 12 shows the distribution of the pedestrian and the background luminance.

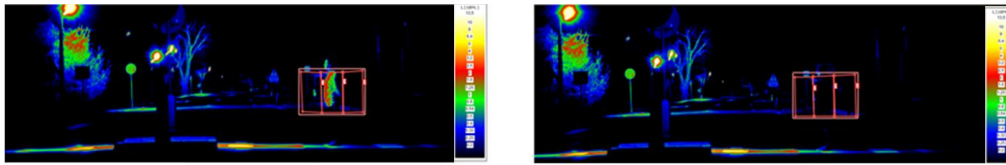


Fig. 12. Distribution of the pedestrian and background luminance for pedestrian crossing no. 3 (light and dark pedestrian clothing – direction 1)

The lack of illumination of the roadway within the pedestrian crossing allowed high contrast and therefore correct visibility of the pedestrian in light clothing. In the case of dark pedestrian clothing, the low vertical illumination values in the crossing area and the lack of road lighting in the vicinity of the crossing resulted in negligible contrast values of the pedestrian, making it impossible to correctly identify the pedestrian in the crossing area. Attention should also be paid to the high contrast value in the waiting zone for the first direction and light pedestrian clothing. The positive contrast value obtained in this case is the highest among all tested pedestrian crossings. This is related to the unlit background in which a pedestrian in light clothing is visible in the waiting zone (Table 4).

Figure 13 shows the distribution of horizontal illuminance for pedestrian crossing no. 4.

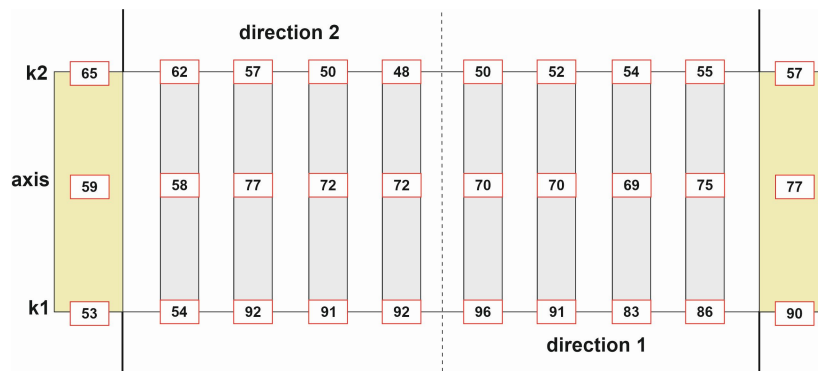


Fig. 13. Distribution of horizontal illuminance for pedestrian crossing no. 4

For the studied pedestrian crossing, more than twice the required (PC3 class) value of horizontal illuminance was obtained. In the case of vertical illuminance, the value obtained was about 20 lx for both directions of traffic and was lower than the required value (35 lx) for the class. It is worth noting the high uniformity for both types of illumination (Tables 2, 3).

Figure 14 presents the distribution of the pedestrian and background luminance for the analyzed pedestrian crossing.

For the studied pedestrian crossing, similar contrast values were obtained for both directions of traffic. For light-colored pedestrian clothing, the contrast was 2.1 for the central crossing area and about 3.5 for the waiting area. Negative contrast values of approx. 0.4 were obtained for the dark clothing, for all the crossing areas studied (Table 4).

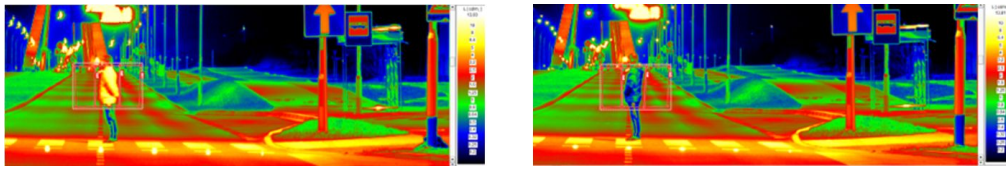


Fig. 14. Distribution of the pedestrian and background luminance for pedestrian crossing no. 4 (light and dark pedestrian clothing – direction 1)

4. Analysis of research results

The results of the pedestrian contrast in the crossing area and the waiting area for the tested pedestrian crossings are shown in Fig. 15. The resulting contrast values are shown for two colors of pedestrian clothing: dark clothing, marked in black on the chart, and light clothing, marked in orange. In addition, the red line shows the threshold contrast limits, above which there is an area of visual comfort and the ability to distinguish details [1, 5].

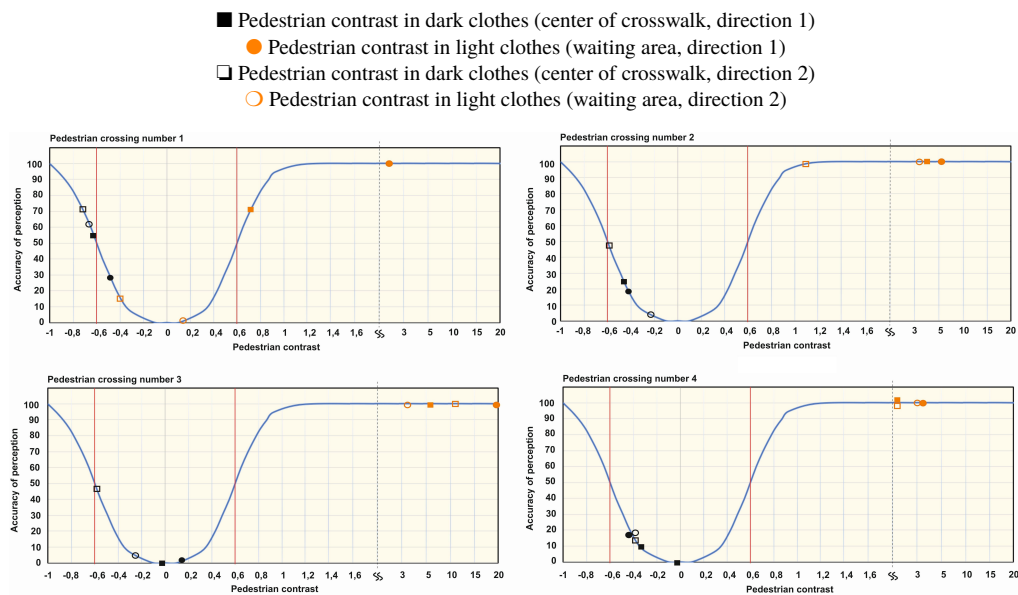


Fig. 15. Pedestrian visibility results for analyzed positive and negative contrast levels

For the first of the studied pedestrian crossings, which was lit only by street luminaires located within the crossing area, high pedestrian luminance contrast above the threshold value was obtained for the selected variants: light-colored pedestrian clothing and the first direction of observation, and dark pedestrian clothing, for both directions of observation of the pedestrian in the crossing area. For the other variants, contrast values obtained made it impossible to accurately see the pedestrian in the crossing and waiting areas.

For the second of the analyzed pedestrian crossings, which was illuminated by street luminaires and additionally by a dedicated luminaire installed directly over the crossing, high values of positive pedestrian luminance contrast were determined for light clothing. These values, above the threshold value, were obtained for both directions of observation of the pedestrian and for both areas considered: crossing and waiting areas. In the case of dark clothing, negative contrast values below the threshold value were obtained, with values for the crossing area, slightly lower than the defined threshold value of -0.6 .

The illumination of the third studied pedestrian crossing was achieved through a D-6 warning sign installed directly above the crossing area, in which an LED light source was placed to illuminate the crossing area in a symmetrical manner. There were no street luminaires near the pedestrian crossing. For the aforementioned pedestrian crossing, high values of positive luminance contrast for pedestrian wearing light-colored clothing were obtained. Such high values, well above the threshold value, were related to the dark background, which included the pedestrian in light-colored clothing, illuminated by a D-6 sign. The situation is different in the case of a dark-clothed pedestrian, who on the dark background was characterized by virtually zero negative contrast, making it impossible to properly see the pedestrian in the crossing area from a safe distance. The pedestrian crossing lighting used, in the form of a D-6 sign placed directly over the pedestrian crossing, does not allow one to produce the required luminance contrast value for pedestrians wearing dark clothing.

For the last of the analyzed pedestrian crossings, which was illuminated with dedicated LED luminaires with asymmetrical distribution, as well as LED street lighting luminaires in the vicinity of the crossing, as in the case of analyzed pedestrian crossing no. 2, high values of positive luminance contrast were obtained for pedestrian wearing light-colored clothing. In the case of dark pedestrian clothing, a negative luminance contrast of about -0.4 was obtained for the analyzed areas and observation directions. This value was slightly below the threshold limit.

Figure 16(a) shows the relationship of pedestrian contrast in the crossing zone as a function of vertical illuminance for the studied pedestrian crossings, while Fig. 16(b) shows it as a function of horizontal illuminance. In the charts, the red line indicates the threshold luminance contrast values, while the green line indicates the required illuminance value for the PC3 class [6], which was defined for the studied pedestrian crossings.

The analysis of the presented relationships does not make it possible to clearly relate the obtained value of pedestrian luminance contrast to the value of vertical and horizontal illuminance.

Only for pedestrian crossing no. 2 was the required PC3 class vertical illuminance value obtained (min. 35 lx). For the aforementioned pedestrian crossing, high positive contrast values were obtained, above the threshold value, but for pedestrians wearing dark clothing, the values were below the threshold value. For the remaining pedestrian crossings, vertical illuminance values of less than 35 lx, as defined for the PC3 class, were obtained. Despite this, for pedestrians wearing light-colored clothing, the desired luminance contrast value of the pedestrian silhouette was obtained in most cases. In the case of pedestrians wearing dark clothing, except for selected cases for pedestrian crossing no. 1, the obtained pedestrian contrast values were below the threshold value.

The analogous situation was in the case of horizontal illuminance, whose value of more than 35 lx was met for pedestrian crossings no. 2 and 4. In these cases, for pedestrians wearing light-colored clothing, a contrast value above the threshold value was obtained, while for dark clothing the values were slightly below the required range. For pedestrian crossings no. 1 and 3 in

which the horizontal illuminance value obtained was below 35 lx, luminance contrast above the threshold value was obtained for light pedestrian clothing in most cases, while for dark pedestrian clothing the value was below the defined threshold in most cases.

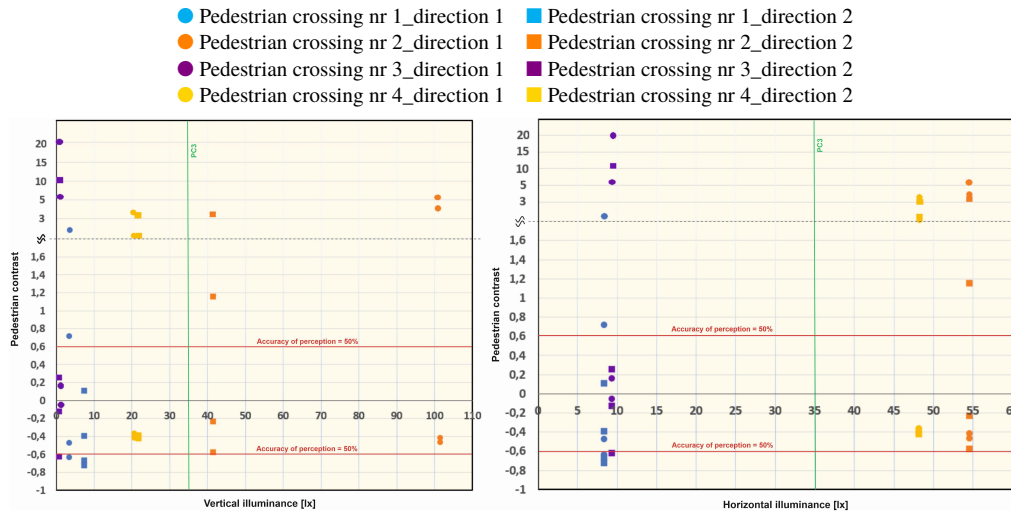


Fig. 16. Chart of the dependence of the pedestrian luminance contrast on: vertical illuminance (a); horizontal illuminance (b)

5. Summary

The article addresses important topics related to the visibility and safety of vulnerable traffic participants in pedestrian crossing areas. In view of the amendment of the Road Traffic Law [32] establishing the right of way for pedestrians within a pedestrian crossing, as well as taking into account the latest guidelines for proper lighting of pedestrian crossings, a study of pedestrian visibility was undertaken for typical, most common pedestrian crossing lighting solutions. For the study, pedestrian crossings were selected whose lighting consisted of street luminaires near the crossing area, luminaires dedicated to pedestrian crossings or the use of both solutions. The obtained values of horizontal and vertical illuminance according to the new guidelines were analyzed, as well as the luminance contrast of the pedestrian against the background, as a determinant of pedestrian visibility in the crossing area.

The obtained research results confirm the currently available publication conclusions and indicate the color of pedestrian clothing as one of the main factors influencing the pedestrian's luminance contrast and, at the same time, his visibility in the pedestrian crossing zone. The biggest problem is dark clothing and the need to create the required negative contrast value to enable the pedestrian to be seen from a safe distance. For the light color of the pedestrian's clothing, a high value of positive luminance contrast was obtained for all analyzed cases of pedestrian crossings, allowing the pedestrian to be seen correctly. For dark-colored clothing, negative luminance contrast was obtained for most of the cases considered, which was lower than the threshold value associated with comfort

and accuracy of perception. In reference to current research results [12] indicating dark colors as the dominant colors in pedestrian clothing during the autumn and winter season, the mentioned aspect is of particular importance in the context of pedestrian visibility and safety in the crossing area. Appropriate lighting of the above-mentioned zones should result in a higher luminance contrast value for dark pedestrian clothing, which translates into greater visibility. The illuminance value should not be too high, so as not to significantly reduce the contrast of light clothing.

It is difficult, unequivocally, to relate the measured values of horizontal and vertical illuminance determined in the area of the studied pedestrian crossings to the obtained value of pedestrian luminance contrast. It is worth noting that for the obtained vertical and horizontal illuminance required for the assumed PC3 class, light-colored pedestrian clothing enabled to obtain the desired contrast value, while for dark-colored clothing the obtained contrast values were slightly below the threshold value. It can be assumed that obtaining the required illuminance values for the appropriate PC classes allows for obtaining appropriate contrast and, therefore, pedestrian visibility for light clothing. In the case of dark clothing, ensuring the above requirements will not always enable the required pedestrian visibility, and creating the appropriate contrast value will also depend on the lighting of additional zones, as mentioned earlier.

Of the available solutions related to the technology and placement of luminaires within the pedestrian crossing, the highest positive contrast values were achieved by luminaires dedicated to pedestrian crossings with asymmetrical light distribution. Simultaneous use of the mentioned solution with existing street luminaires also results in the possibility of obtaining the desired values. The use of pedestrian crossing illumination in the form of a D-6 sign installed directly over the crossing made it possible to achieve a high positive contrast value. With the pedestrian's dark clothing, the value of the contrast was practically zero, creating a high risk of not seeing the pedestrian within the crossing area. The presence of only street luminaires within the pedestrian crossing area, also makes it possible to produce adequate lighting conditions and pedestrian luminance contrast within the pedestrian crossing, as confirmed by the study of pedestrian crossing no. 1. The contrast value obtained, however, will depend on the placement of the street luminaire relative to the pedestrian crossing and the light distribution used. In this case, the desired values will usually be met for only one direction of observation. The use of only street luminaires located in the appropriate crossing zone can be considered in the context of one-way roads, and the above solution makes it possible to create an appropriate pedestrian contrast in the direction of driving of motor vehicles. In the case of the most common variant of two-way roads, the most advantageous solution is to use dedicated lighting with asymmetric distribution, enabling the creation of contrast for both directions of traffic.

Based on the results of the study, it can be concluded that the developed pedestrian luminance contrast value, in addition to the provided lighting conditions at the pedestrian crossing and the obtained illuminance value, depends mainly on the color of the pedestrian's clothing and the background luminance within the crossing area. The aforementioned factors should be taken into account in the design of lighting individually for each pedestrian crossing under consideration. It also seems sensible to be able to adequately illuminate not only the crossing area itself, but also the area behind the pedestrian crossing to produce the desired negative contrast value. To increase the visibility of pedestrians in crossing zones, it seems reasonable to undertake research on a lighting system operating in real time, enabling adaptation to the current situation within the pedestrian crossing. The system should continuously analyze the crossing zone, the color and

the resulting luminance of the pedestrian's clothing, and then appropriately increase or decrease the lighting intensity in the zone before and behind the crossing, generating the required contrast value enabling the pedestrian to be seen from a safe distance.

The presented research results cover only a part of the issues and problems related to pedestrian crossing illumination, as well as the measurement of parameters and indicators that determine the visibility of the pedestrian in the crossing area. Further studies covering the above topics related to the safety of vulnerable road users at pedestrian crossings are planned.

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