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Smart traffic light system for increasing the pedestrian safety

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Abstract

Smart traffic lights are the main component of smart city lighting for providing its sustainability. In combination with new technologies that allow saving energy and using intelligent lighting control, the best performance can be achieved. Creating safe conditions for all road users is the key to preserving their health and reducing the number of traffic accidents on the roads. Unfortunately, this cannot guarantee safety for pedestrians when crossing a wide high-speed and busy road or waiting in the zone of a pedestrian refuge island (PRI). The most applied construction of a refuge island in modern cities consists of traffic lights and small concrete limiters nearby both sides of a PRI or two metal bollards without traffic lights. Such type of PRIs cannot defend the pedestrians from vehicle accidents in case of rapid car movement towards the island zone because of destruction or unavailable speed and direction of vehicle. The probability of accident with a pedestrian victim is higher at night, that is why the application of metal bollard without lighting cannot provide enough of its visibility for drivers at dusk or later in the evening. Based on the review of studies, an optical system of bollards, which are on the market and used for traffic management, is not considered in any work. Therefore, to improve the visibility of the bollard, a design of the bollard with a fundamentally new optical system is proposed. Based on the aforementioned grounds, the purpose of this paper is the consideration of ways to increasing the safety for PRIs construction in a smart city. This problem can be solved by using a bollard with a lighting block for its detection by drivers given limited visibility in the evening. In the paper, the construction of a PRI with a bollard, with an improved optical block with low-powered LEDs, has been suggested and analyzed.

Keywords: street lighting; signal bollard; refuge islands.

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Introduction

The rapid urban growth, changes in the rhythm of people's life and activities lead to increased requirements for lighting of transport routes to ensure comfort and safety of city residents at night, sufficient level of road lighting for drivers and pedestrians, as well as creating a unique evening view of the city. At the same time, there is a growing need for intelligent and high-quality traffic management during the day and night. This is crucial for both motorists and pedestrians. And first, this applies to young people: school and university students, whose faces are virtually glued at the screens of phones and tablets while driving, as well as the elderly and people with visual impairments.

According to Statista data (Fig. 1), the increase in car sales is the cause of traffic jams when drivers try to speed up, so in some cases they violate traffic rules, which in turn can lead to accidents.

According to the data of the patrol police [2], the statistical compilations on traffic accidents with victims in Ukraine for the last year, given a full-scale military invasion in Ukraine, bear many nuances and do not take into account all traffic accidents compared to previous years. The hostilities and occupation do not make it possible to take into account the data from the Donetsk, Luhansk, Kharkiv, Zaporizhzhia, Kherson, and Mykolaiv regions. The most common types of road collision fatalities are collisions ~ 41%, collisions with pedestrians ~ 29%, collisions with obstacles ~ 13%.

Based on statistical data, the number of road accidents increased by 38% in 2023 compared to 2021 (before the full-scale invasion).

Therefore, the purpose of the paper is to increase the pedestrian safety by application of the improved protective element (a bollard), for the organization of pedestrian crossings. It is shown how the element

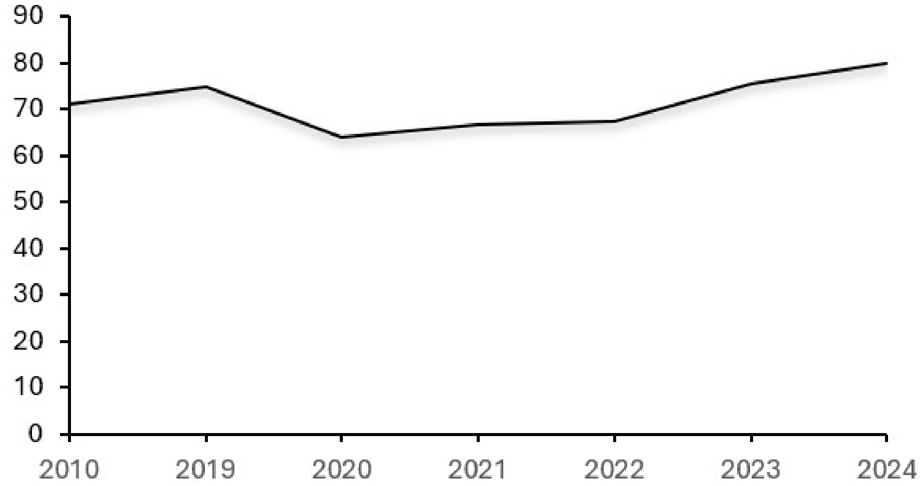

Fig. 1. Global car sales from 2010 to 2024 (in million units) [1]

Table 1

Statistics of traffic collisions in Ukraine (2019–2023)

Year	2019	2020	2021	2022	2023
Traffic collision fatalities and injuries	3454	3541	24521	18628	63642
Deaths	3454	3541	3238	2791	3053
Types of traffic collision:					
Collision with vehicles	10563	10946	10376	7387	9792
Collision with pedestrians	2574	7641	7509	5284	6499
Collision with obstacles	8612	2809	2508	2477	2918

can be effectively used for dividing lanes or refuge islands, and also be used as an auxiliary means for traffic regulation that duplicates the signal of the main traffic light, which will in turn increase the safety of pedestrians and cyclists when crossing the roadway and minimize the number of possible traffic accidents.

Study of smart traffic lights systems

The influence of road lighting parameters and types of intersections on creating comfort visual and safety space for pedestrians and drivers were considered in different ways. Hongtao Li, Linhong Wang, Hongyu Hu, Yiming Bie [3] studied the optimal correlation between the car speed and the lighting system parameters at the intersection based on the analysis of traffic risks. In [4], the authors studied the interactive effect of vehicle headlights in combination with intersection lighting on the contrast of objects. Cyber-physical systems for intelligent traffic light control that use traffic detection cameras, machine learning algorithms, and a ladder logic program were analyzed in [5–8]. The method of adjusting the traffic light signal intervals based on real-time traffic data and the information about pedestrians and vehicles is proposed in [5]. The scheme of the method is presented in the Fig. 2.

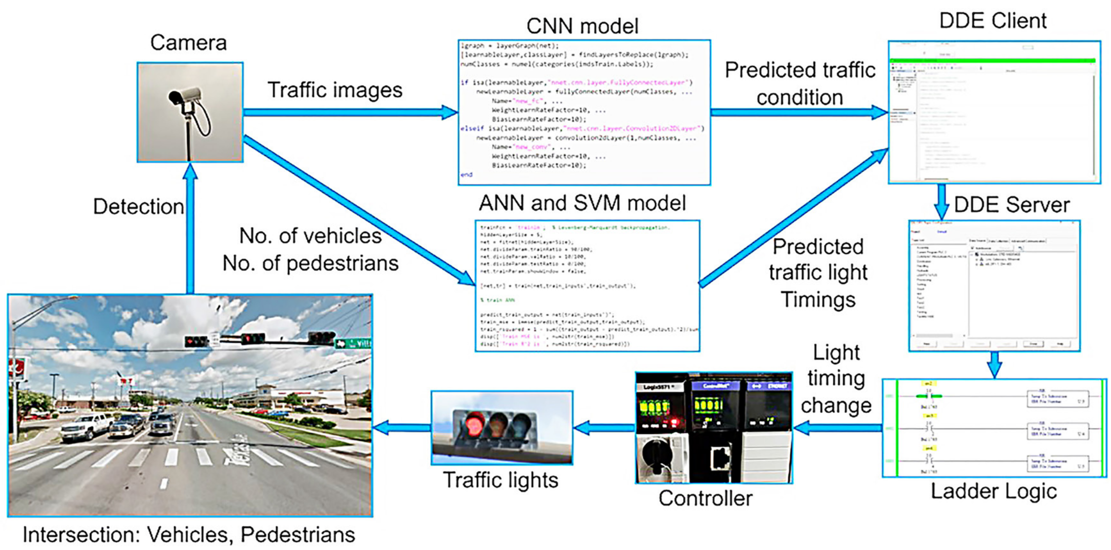

Fig. 2. Intelligent traffic light control system [5]

Fig. 3. Types of bollards for traffic management: a) J200 HA H600 Hydraulic Automatic Retractable Residential Traffic Control Security Bollard (Painted Steel) – FAAC 116500 [13]; b) Manufacturer Sale HA101-800 Hydraulic Automatic Bollard [14]; c) R-6101 Crosswalk Bollards; d) R-7582 Decorative Bollard [15]

The simulation results indicate that the dynamic traffic spacing method is more efficient and demonstrates a 12–27% reduction in vehicle waiting time and a 9–23% reduction in pedestrian waiting time at the intersection compared to fixed time and semi-dynamic traffic light control methods. Traffic lights are applied to regulate traffic at road intersections. The control mechanism works according to a fixed periodic schedule, according to the change of light (red/yellow/green). The authors of [6] claim that such fixed light control does not respond to changes in traffic conditions and does not take into account traffic jams. They propose a new structure of dynamic control of traffic lights at road intersections. The proposed dynamic traffic light control framework relies on a network of sensors to collect traffic data and includes new protocols to tackle traffic jams and promote more efficient traffic flow. The proposed low-overhead algorithms are practical for use in live traffic scenarios [6].

A new approach to optimal management of pedestrian safety at pedestrian crossings by integrating pedestrian detection and synchronized control of traffic light signals with automatically retractable columns is considered in [7]. The system uses computer vision-based pedestrian detection techniques to accurately identify pedestrians in real-time, allowing the allocated phases of the crossing to be allocated. With the subsequent activation of retractable bollards, a physical barrier to prevent vehicles from entering the crossing is created, thus increasing the pedestrian safety. Synchronization between the bollard activation and traffic signals ensures a coordinated interaction between pedestrians and vehicles, improving the overall efficiency of the traffic flow. Many works, [8–10], are dedicated to the study of the perception of road lighting taking into account mesopic vision, which is significantly influenced by the S/P ratio of light sources used in the designed system. Other works, [11, 12], consider the system of organizing a pedestrian crossing with retractable bollards in terms of compliance with traffic rules by both drivers and pedestrians. Existing bollards on the market differ in design and purpose (see Fig. 3). Those used for traffic management have significant structural disadvantages (the presence of an automatic drive that helps lower and raise a bollard (Fig. 3, a, b) [13, 14]). Reliance Foundry offers polyurethane pedestrian bollards ((Fig. 3, c) [15], which can bend during an impact and then return to their initial position, as well as conventional boundary bollards. These bollards have reflective tapes.

Based on the review of the studies, optical systems of medium-sized light-signal type bollards, which are

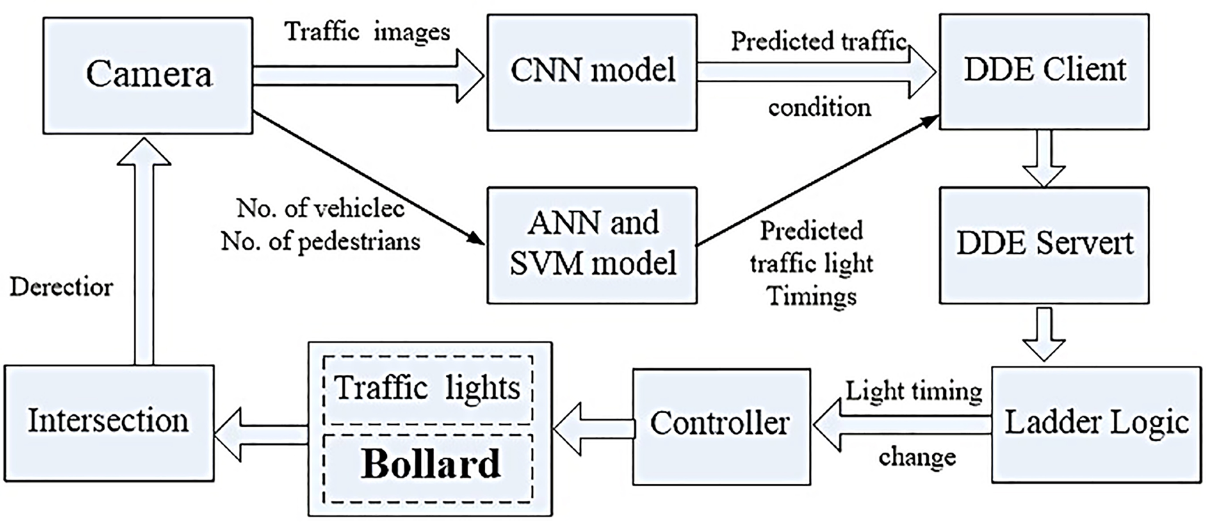

Fig. 4. Smart traffic lights system for increasing the pedestrian safety

on the market and are intended for traffic management, are not considered in any of the works. Therefore, to improve the visibility of the bollard, a design of the bollard with a fundamentally new optical system is proposed [16]. The advantages of the proposed bollard construction are: increased pedestrian safety on the crossings and intersections; additional signal allows ensuring the awareness of drivers because of increasing visibility of refuge islands; additional mechanical elements prevent from vertical hamming; the use of LEDs as light indicators allows integrating the bollards into smart traffic lights system (see Fig. 4).

Proposed design of a light signal bollard

Due to the increase in the number of vehicles and the speed of traffic in settlements, safety structures for pedestrians crossing the roadway have been strengthened. In particular, the mandatory installation of refuge islands on unregulated pedestrian crossings across a roadway with 4 or more lanes has been introduced. A pedestrian can conveniently cross the first part of the crossing, safely wait in the island zone, and continue the way. At the same time, even in the island zone, it is necessary to protect pedestrians from accidental collisions, which, unfortunately, still happen. The main task of an anti-collision bollard is to guarantee a stop of the car, preventing it from moving further. In addition, light bollards installed on dividing lanes or refuge islands are used as an auxiliary means of traffic regulation, useful for inattentive pedestrians or people with visual impairments. The development is aimed at solving these problems. Bollards refer to traffic control systems installed in places with a high probability of a traffic accident involving pedestrians as a protective element on dividing lanes or refuge islands and are also used as an auxiliary means duplicating the signal of the main traffic light. The model is based on the task of improving the design, operational characteristics, and increasing efficiency of the bollard. The traffic light bollard consists of a metal body, inside which a light source in the form of two LED pairs (green, red) is placed. The LED unit is located on diametrically opposite sides of the metal body, under a round diffuser at the focus of round parabolic mirrors, which are bisected and reflected on the diffuser. Fig. 5 shows a possible design of the bollard.

The metal body (1) is usually made of a pipe with a wall thickness of 12 mm or more. From above, the metal body is closed with a cover (5). To increase the protective function, the inner part of the pipe, not occupied by optics, can be filled with concrete. Inside the metal body (1), there is an LED light source (2) made of two LEDs (green and red). The optical design of the right and left sides of the bollard are the same. The LEDs are installed on the heat sink below the diffuser (4) in the focus of the bisected circular parabolic mirror (3). As a light source, you can use, for example, green and red LEDs Foton LED 5W Green,

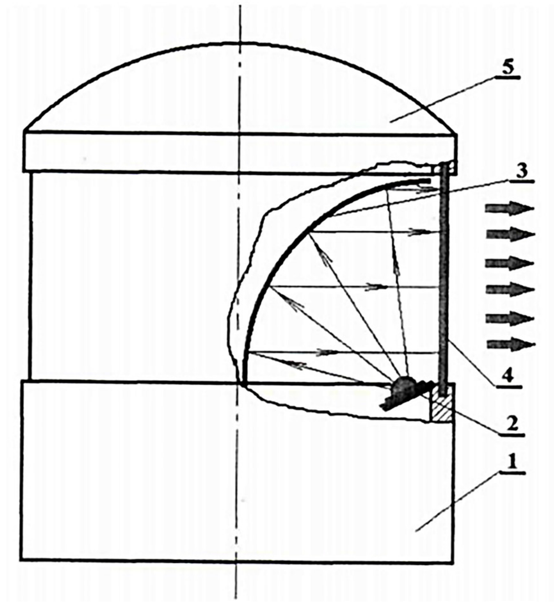

Fig. 5. The optical system of the developed bollard: 1 – metal body; 2 – LED light source (green and red LEDs); 3 – bisected circular parabolic mirror; 4 – diffuser; 5 – bollard cover

517–520 nm BIN1, Foton LED 5W Red, 625–630 nm BIN1, which have a luminous flux in the range from 200 to 300 lm and the beam angle is within 130°. The parabolic mirror is installed in front of the diffuser so that its lower part (the part on which the mirror is bisected) is parallel to the lower border of the diffuser (4). For the bollard, diffusers should be used made of ultraviolet-resistant material – matte, semi-matte, depending on the specific design. The light from the working LED is directed to the parabolic mirror (3), which forms a parallel light stream and directs it to the diffuser (4). The use of a parabolic mirror in the formation of a light stream ensures high visibility of the bollard signal, duplicating the operation of the pedestrian traffic light, at long distances.

If the pedestrian traffic light works for two lanes, that is, a pedestrian can cross both traffic lanes at the same time, then the LEDs of the same colour on the left and right sides of the bollard are turned on at the same time. If the pedestrian traffic light in the zone of a refuge island works separately for each traffic lane, in this case, turning on the LEDs in the left and right sides of the bollard is synchronized with the operation of the pedestrian traffic light for the corresponding lane. Usually, two or four bollards are used in the zone of refuge islands. In case of using four bollards in the zone of refuge islands, only one optical side is used in the design of the proposed bollards, directed towards the traffic lane, which ultimately leads to a reduction in costs.

So, in our opinion, the proposed design of the light signal bollard will improve the operational characteristics, in particular, increase the visibility of the bollard signal due to the use of a parabolic mirror, which also allows reducing the power of the LEDs used in the optical circuit and leads to energy

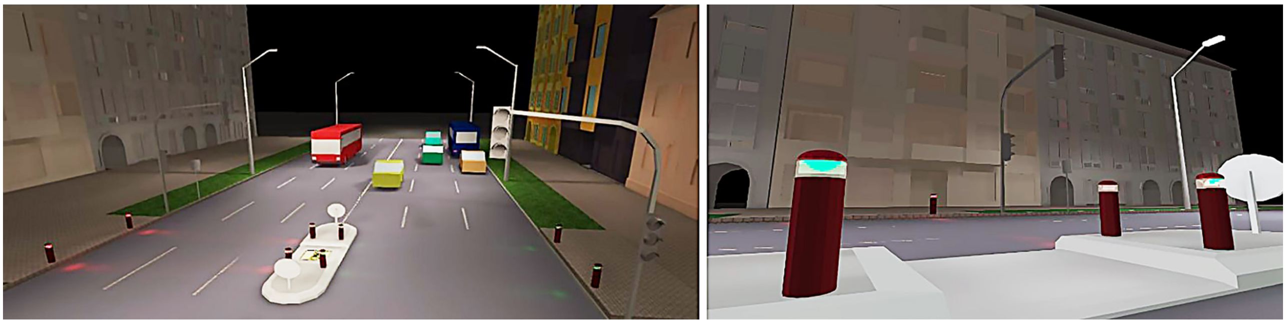

Fig. 6. Visualization of a street section in the zone of a refuge island and a pedestrian crossing

savings. In addition, the useful model makes it possible to increase the efficiency of using the bollard in the zone of a refuge island considering the fact that it can be used both when the pedestrian traffic light works simultaneously for two lanes, and separately for each lane.

Modelling a highway lighting system with light bollards

To assess the lighting conditions of pedestrian crossings and refuge islands, a simulation of a lighting scene (A3 category or M3 class streets) was performed using the proposed design of light bollards when installed in the zone of refuge islands as shown in Fig. 6. For this, a bollard was separately created in DIALux evo 13.1 according to the design described above, taking into account the power of the LEDs, the colour of their radiation and fixing in bollards, and for realistic light distribution, a mirror parabolic reflector was added to the scene element (bollard) to increase the efficiency of this light device (as specified in [16]).

When analyzing the characteristics of a light environment defined in DIALux 13.0, the requirements of current Ukrainian and European standards [17, 18], given in Table 2, regarding the lighting of transport routes and the location and value of the characteristics of the distribution of horizontal and vertical illuminances at control points, were taken into account and met.

To provide general lighting for the street of the specified category, lighting options with LED luminaires manufactured by Schréder with the characteristics specified in Table 3 were considered, which are located in the opposite pattern along the roadway of the road with a support pitch of 30 m, with a height of the light centres of the luminaires of 9 m.

Table 2

Standardized characteristics of pedestrian crossing zones in accordance with Ukrainian and European standards

No	Characteristic name	DBN 2.5-28-2018 for A3 category of street	EN 13201:2015 for M3 class street	EN 13201:2015 (Czech Republic)
1	Average horizontal illuminance, lx	30	20	30
2	Minimum horizontal illuminance, lx	15	–	20
3	Average vertical illuminance, lx	–	50	50
4	Luminance according to category or class, cd/m^2	1.2	1	0.75–1

Table 3

Comparative characteristics of street lighting options

Characteristic name	AXIA 3.3 5281	AMPERA MAXI 5239
Power, W	115	132
Efficiency, %	88	86
Maximum service life, thousand hours	up to 100000	up to 100000
Control protocol	DALI	DALI
Colour temperature, K	4000	4000
Power Density Indicator (PDI), W/(lx×m^2)	0.02	0.01
Annual Energy Consumption Indicator (AECI), kW/m^2	0.13	0.14
Average roadway luminance, cd/m^2	1.54	2.05
Horizontal crosswalk illuminance, lx	32.6	43.6
Vertical crosswalk illuminance, lx Average Maximum	 29.3 38.6	 30 50.6

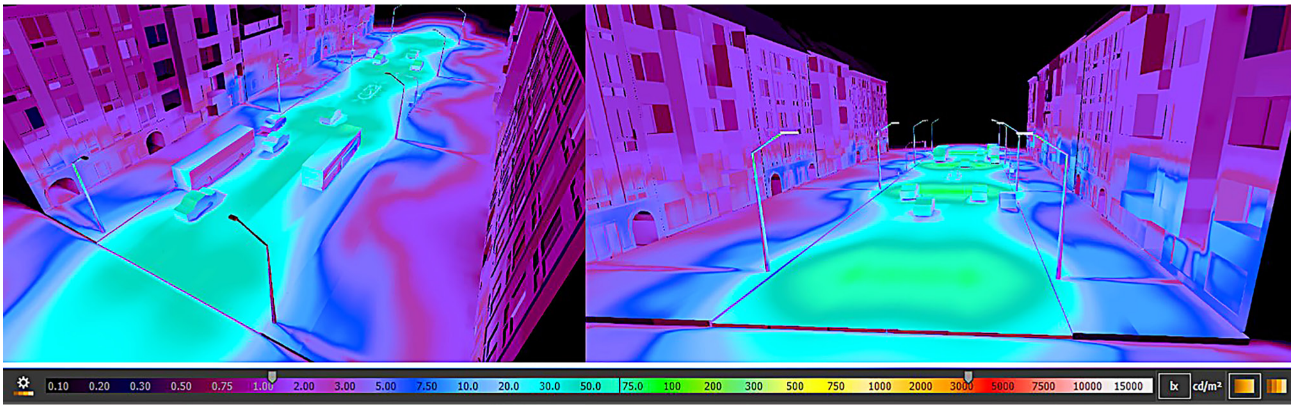

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Fig. 7. Distribution of illuminance on the road surface for two lighting options with luminaires: a) AXIA 3.3 5281; b) AMPERA MAXI 5239

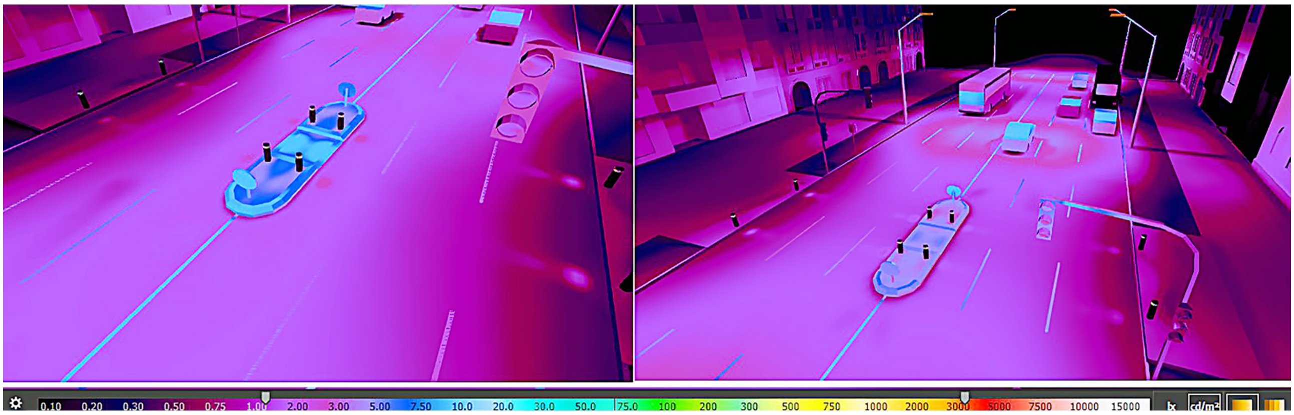

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Fig. 8. Distribution of luminance on the road surface for two lighting options with luminaires: a) AXIA 3.3 5281; b) AMPERA MAXI 5239

Figs. 7–8 show the results of calculating the distribution of illumination and luminance over the surface of the roadway.

Comparison of horizontal, vertical illuminances and luminances of the pedestrian crossing model in DIALux evo 13.0 for two lighting options confirmed that their main parameters meet the requirements of European standards and create a comfortable light environment.

The conclusions

Based on the results of modelling the distribution of luminance and illumination of the roadway, as well as vertical illumination, the following conclusions can be drawn:

1. The application of light signal bollards allows increasing the level of luminance and illuminance of the pedestrian crossing zone and makes it possible to increase the safety of pedestrians and drivers due to additional protection against accidental collision with a refuge island.

2. The use of LED radiation sources in these light signal devices allows their integration into an intelligent control system for traffic light systems and a smart city as a whole.

3. Determination of PDI and AECI energy efficiency indicators of the proposed system of outdoor lighting of transport highways with refuge islands and light signal bollards confirmed its high energy efficiency.

4. Detailed modelling of the proposed design of a light bollard made it possible to more accurately take into account their impact on the lighting parameters of the light environment and increase the realism of the visualization of a street section, which provided the possibility of a more accurate assessment of the energy efficiency of the street lighting system as a whole.

5. Due to the proposed design of the bollards, this device is an effective means of duplicating traffic light signals and a high-quality light element that does not create a glare effect for drivers and pedestrians with high energy efficiency.

Thus, the bollard can be effectively used as a protective element for pedestrians on dividing lanes or in the zone of refuge islands and can also be used as an auxiliary means for traffic regulation that duplicates the signal of the main traffic light, which will increase the safety of pedestrians and cyclists when crossing the roadway and minimize the number of possible traffic accidents.

Розумна світлофорна система для підвищення безпеки пішоходів

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Анотація

Розумні світлофори є основним компонентом розумного міського освітлення для забезпечення його стійкості. У поєднанні з новими технологіями, які дозволяють економити енергію та використовувати інтелектуальне керування освітленням, можна досягти найкращої продуктивності. Створення безпечних умов для всіх учасників дорожнього руху – запорука збереження їхнього здоров'я та зменшення кількості дорожньо-транспортних пригод. Але, на жаль, ця установка не може гарантувати безпеку для пішоходів, коли вони перетинають широку високошвидкісну та інтенсивну дорогу або чекають на пішохідному острівці безпеки (PRI). Найбільш поширена конструкція острівця безпеки в сучасному місті складається зі світлофорів і невеликих бетонних обмежувачів по обидва боки PRI або двох металевих стовпчиків без світлофора. Такі типи PRI не можуть захистити пішоходів від ДТП у разі швидкого руху автомобіля в острівну зону через руйнування або недоступність швидкості та напрямку транспортного засобу. Ймовірність ДТП з потерпілим пішоходом вища в темний час доби, тому застосування металевого стовпчика без освітлення не забезпечує достатньої його видимості для водіїв у сутінках або пізно ввечері. Зважаючи на огляд досліджень, оптична система болардів, які є на ринку і використовуються для організації дорожнього руху, не розглядається в жодній роботі. Тому для покращення оглядовості боларда пропонується конструкція боларда з принципово новою оптичною системою. На підставі вищезазначених міркувань метою статті є розгляд шляхів підвищення безпеки будівництва PRI в розумному місті. Розв'язати цю проблему можна за допомогою боларда з освітлювальним блоком для його виявлення водіями при обмеженій видимості у вечірній час. У роботі запропоновано та проаналізовано конструкцію PRI з болардом, що має вдосконалений оптичний блок зі світлодіодами малої потужності.

Ключові слова: вуличне освітлення; світлосигнальні боларди; острівці безпеки.

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