Advanced Controlled Road Lighting System Concurrent with Users

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Abstract: The operation of a concurrent lighting system using LED luminaires is based on the detection of individual road users, the recognition of their lighting needs and adjusting the operating state of the individual lighting devices that make up the system to the expectations of each user. The luminaire’s lighting divided into three independently controlled parts allows reducing electrical energy consumption up to 33% in comparison to a conventional concurrent road lighting system.

Keywords: road lighting; lighting equipment; lighting control

1. Introduction

One of the most significant, if not the most significant, tasks that science faces today is reducing greenhouse gas emissions into the atmosphere, dictated by the concern for the environment that is being increasingly degraded, in particular by climate change. One way greenhouse gas emissions are reduced is by decreasing the consumption of electric and thermal energy, especially those produced from fossil fuels [1].

For several years, there has been an intensification of research in the area of increasing the efficiency of energy conversion and use. Another second clear trend has been to reduce the energy wasted on the unproductive operation of electrical equipment. The same trends can also be observed in research on electric lighting [2–4]. On the one hand, increasingly more effective light sources and highly efficient luminaires [5] are being developed; on the other hand, control systems are being introduced both in buildings [6] and in outdoor lighting [7], allowing for more economical use of electric energy [8]. Unfortunately, some of the proposed solutions lead to a minimization of lighting conditions and force the user to perform intensive visual work at the limit of efficiency [9].

However, lighting systems exist that reduce electricity consumption while meeting the lighting needs of users at a sufficiently high level. These include all systems based on low-energy-cost detection of each user and subsequent reduction in illumination in zones where no user is found. Such systems may include but are not limited to concurrent lighting of vehicle, bicycle and pedestrian traffic roads or paths. Concurrent lighting systems have already seen various implementations and proved to be highly efficient [7,10–12]. However, they still may be improved and their performance enhanced, thereby increasing their efficiency in saving electricity.

In recent years, the approach to the design of luminaire optics has also changed. Modern luminaire design is no longer about obtaining that distribution of the luminous flux for which it is possible to find the distribution of light points in which the lighting requirements are met. Nowadays, we seek to find such distributions that allow us to meet the lighting requirements in an optimal manner, that is, most often with a minimal luminous flux expenditure in the particular boundary conditions of the distribution of light points [13].

This way of designing luminaires allows for far-reaching optimization of the lighting device. This paper will present the idea of a luminaire that, thanks to the use of modern
design tools, allows more efficient energy management, thus making concurrent lighting systems even more economical and ecological.

2. Concurrent Lighting System

The operation of a concurrent lighting system, dedicated for lighting using LED as light sources, is based on the detection of individual road users, the recognition of their lighting needs, and the adjustment of the operating state of the individual lighting devices that make up the system to the expectations of each user [14]. The quality of the system operation primarily depends on the quality of the detection of a single user, the accuracy of determining their needs, and the appropriate dissemination of the collected information between all elements of the system. The quality of user detection depends on the system of different sensors that is used. The concurrent lighting system was created based on the lighting requirements and the road lighting design method used in Europe. The lighting needs of people performing various activities in public open spaces have been accurately identified and described by the provisions of the relevant standard [15]. The analysis of these needs in terms of their feasibility in a concurrent system is presented in the next section.

The solutions that have, until recently, been used to control luminaires in a concurrent system assume control of entire luminaires without the possibility of dividing the luminaire into independent sections. Along with the movement of the user, individual luminaires are lit when the user approaches them or are dimmed and deactivated when the user moves away. The number of lit luminaires depends on the type of user (pedestrian, cyclist, car driver), their speed and the predefined system settings that result from the location of the individual points of light in the area. It should be remembered that the user must be detected in advance so that the system can react to it in a timely manner. For this reason, it is very important to transmit information about the current position of individual users between sensors and luminaires, sometimes located at a considerable distance from each other.

The system is able to adjust those parameters that influence the behavior of the system, such as the maximum distance between two users that causes all the luminaires between them to be lit, the length of the lit road section in front of and behind the user, and the speed of the luminaires lighting up and dimming. These parameters cause different behaviors of the different applications of the system, especially when the presence of two or more users coincides.

The advantage of a concurrent system over other lighting control systems is that it provides the same lighting conditions to all users, regardless of the time when they move along the street. Dimming systems have the disadvantage that they provide much more light to users at times when there is more traffic, i.e., they meet their needs at a higher level than with users who appear at times when the traffic intensity significantly decreases. In a sense, luminaire dimming systems discriminate users who are in the minority [10,16,17]. A concurrent lighting system could be combined with the idea of dimming lighting at times when traffic intensity decreases to introduce additional energy savings, but such an idea conflicts with the idea of treating all users equally.

Due to the dynamics of the system, it is not possible to use it everywhere. The selected luminaire in the system is controlled not only by the signal of the sensor placed in it but also reacts to information sent from neighboring luminaires, some of which may be several hundred meters away. Therefore, it is necessary to introduce zones for detecting an approaching user on the periphery of the area covered by the system. In particular, it is necessary to pay attention to the “run-up” zones at the beginning of the road sections where the system is applied. Such a section must have a length not shorter than the typical distance of observation of the road by the driver, which is at least 60–100 m. For this reason, it is assumed that the length of a road section covered by the system, in order for its construction to make sense, should not be less than 1 km.
Another limitation to the applicability of the system is the anxiety the system may cause in potential side observers. Therefore, the system should not be used for roads immediately adjacent to residential buildings. Between the section of the road illuminated by a concurrent lighting system and the residential buildings, there should be an impediment that limits the negative impact of the system’s operation on the well-being of the residents. Such impediments may include an appropriate physical distance between the concurrent lighting system and residential buildings, a strip of medium and high greenery, or another traffic route that is illuminated continuously. According to the surveys conducted, concurrent lighting is acceptable on roads directly adjacent to residential buildings only on the condition that traffic practically ceases to exist at late night hours. Moreover, it requires a careful selection of the luminous flux distribution by the luminaires used.

The third factor limiting the applicability of the system is the continuation of high traffic levels on the given road around the clock, including late at night. In the case of such roads, installing the system will not bring tangible benefits. The luminaires, despite correct user detection and control algorithms, will operate continuously and at maximum power for most of the time, with only minor interruptions occurring during traffic fluctuations.

The energy effects of concurrent lighting systems depend on the density of traffic in the area covered by the control system, the synchronization of users, the calculating level of lighting at full power of all luminaires, and the level to which lighting is reduced when there are no users within the range of lighting provided by the luminaire.

Lower traffic intensity during the operation of the lighting device causes correspondingly prolonged breaks in the lighting of the luminaires. The frequent occurrence of such interruptions and their long duration significantly reduces the energy consumption of the lighting system controlled with the use of such a method. Similarly, the grouping of several users moving in the same direction at a similar speed means that a single luminaire simultaneously serves to fulfil the lighting conditions dedicated to a number of users. The grouping of users at a given traffic level results in longer lighting intervals between the successive groups. The longer the required distance of the illuminated road ahead of the user, the more effective the grouping effect is.

A factor that reduces the savings effect is the presence of objects requiring permanent lighting on the road, such as intersections of traffic routes with both vehicle and pedestrian traffic.

3. Advanced Road Lighting System

3.1. Lighting Needs of Road Users

Street lighting is used to ensure proper viewing conditions for people using the streets. Designing in the so-called multi-criteria design process also takes into account other factors such as electricity consumption and, indirectly, environmental pollution through CO₂ emissions into the atmosphere and light pollution of the environment; however, the needs of users are paramount. A good lighting design requires the fulfilment of basic criteria related to the comfort of the users’ vision, with the lowest possible negative impact of the lighting device on the environment [18,19].

Non-motorized users, such as pedestrians, joggers, in-line skaters, scooter riders and cyclists need lighting for general orientation and to recognize an uneven road surface directly in front of them in order to be able to move safely in a stable way, and for information about the position (approaching) of other people or vehicles. For this reason, they need well-lit immediate surroundings, a slightly weaker illumination of the further surroundings and an indication of the position of other people and animals in the area. An important role of lighting traffic routes for non-motorized persons is to enable them to recognize the face of the person they encounter. The lighting requirements for this type of user are defined by the illuminance level at the ground level and a semi-cylindrical illuminance level at face height. The lighting should be non-directional and reach the illuminated object from a minimum of two directions.
Motorists generally move in two opposite directions and need illumination to identify possible obstacles and to identify other traffic users. Due to the typical nature of the reflective properties of road surfaces, lighting is designed to achieve negative contrast, i.e., an obstacle on the road is to be seen as a dark spot on the bright surface of the pavement. In this approach to lighting, it is extremely important to achieve an appropriate level and uniformity of pavement luminance. It is known from design practice that this effect is best achieved when the luminaires are placed directly behind the obstacle from the observer’s point of view [20]. A detailed analysis of the influence of the luminous flux distribution from the luminaire on the luminance distribution of the pavement shows that the luminous fluxes directed in the same way as the user’s observation of the road have an insignificant, practically negligible, effect in creating the desired luminance distribution of the road surface.

Objects that are outside the area of the road but in the immediate vicinity should be visible to drivers in positive contrast, that is, as bright spots, visible against the dark background of the roadside.

Virtually all of the pavement luminance of the road segment located between two adjacent lampposts originates from the luminaire located at the end of that segment. The lamppost located at the beginning of that section is relevant only for the small initial zone of that section, located directly below the lamppost. The size of this zone depends on the detailed reflective properties of the pavement material and, of course, the placement of the luminaires along the road.

Typical, asymmetrical distributions of luminaires commonly used to illuminate roads, as shown in Figure 1a, were compared with the distributions of non-symmetrical luminaires, meeting the required luminance distributions from the observation point of only one of two typical computational observers, as shown in Figure 1b [21]. For comparison, the distributions of both types of luminaires were chosen, whose placement allowing the meeting of the lighting requirements was identical. The course of the light curves of both types of luminaires in their considerable part overlap. The main difference in the course of the curves is observed in the part serving the asymmetrical luminaire to produce the required luminance distribution from the point of view of the second computational observer. The difference in the luminous fluxes between the two distributions is typically about 30% of the flux of the asymmetrical luminaire in favor of the non-symmetrical luminaire.

Using the relationship between asymmetric and non-symmetric luminaires described above, it is possible to conceptualize an asymmetric luminaire, which, for individual users, will behave like a non-symmetric luminaire, generating the same luminous flux and electrical energy savings. Such a luminaire should have a variable luminous flux distribution that adapts to the needs of the current users. When a user approaches from the left or right, the luminaire should generate a non-symmetrical distribution towards the user. When two or more users approach from both sides, the luminaire should generate an asymmetric one.

3.2. Three-Zone Luminaire

The luminaire’s lighting unit, whose light source is a set of light-emitting diodes, has been divided into three independently controlled parts emitting similar luminous fluxes, however, each with a completely different distribution, marked as left (L), central (C), and right (R), as shown in Figure 2. The distributions of the left and right parts are mutually symmetric. All three parts of the luminaire illuminated at the same time realize the full luminous distribution, characteristic for road lighting luminaires, and meet the lighting requirements for all traffic users with the particular distribution of the light points. The left and middle parts lit together, with the right part switched off, realize the non-symmetrical distribution, which allows meeting the criteria for lighting requirements for users approaching from the left side. The right and central parts lit together, with the left part switched off, make the non-symmetrical distribution, allowing it to meet the lighting requirements for users approaching from the right.
Figure 1. Asymmetrical light density distribution of a typical road luminaire (a). Non-symmetrical light density distribution of a road luminaire meeting the required luminance distributions from the observation point of one of two typical computational observers (b).

Figure 2. Division of the luminaire photometric solid into left (L), center (C), and right (R) sections.

The expected luminous flux distribution of the left or right parts should be determined as the difference between the distribution of the asymmetrical and non-symmetrical luminaires, respectively, meeting the lighting requirements for an observer to the right or left of the luminaire, respectively, when the luminaires are spaced in the same way. The expected distribution of the central part may be calculated by first determining the distributions of the side parts, left and right, and by subtracting them from the distribution of the asymmetrical luminaire.

As a result of such operations, we obtain two mutually symmetrical light distributions of the luminaire side parts, oriented quite narrowly to the left and right side respectively, and the light distribution of the central part, illuminating the area located directly under the luminaire and the roadside (Figure 3).

During the design of a luminaire intended for the implementation of an advanced concurrent lighting system, special attention should be paid to the proper illumination of the roadside and, in particular, the objects located on it, which, in contrast to the objects located on the road surface, are seen in positive contrast (bright objects on a dark background of the roadside). See Figure 4.

Such a luminaire operating in an advanced lighting system must receive more information than a classic luminaire controlled uniformly throughout. To take full advantage of its capabilities, it is not enough to inform it that a user is approaching and the light needs to be turned on or that a user has just passed by and that another user is not approaching, so the light needs to be dimmed. A three-zone luminaire needs additional information—which side the user is approaching from. This information is then transformed into information
as to which parts of the luminaire should be switched on at a given moment and which parts should remain switched off and for how long.

Figure 3. Luminous flux density distribution of the left part of the luminaire (a). Luminous flux density distribution of the central part of the luminaire (b). Luminous flux density distribution of the right part of the luminaire is symmetrical to (a).

As shown in Figure 5, if the user is approaching a particular luminaire from the left, the left and center sections are illuminated. If the user approaches from the right, the right and center parts are illuminated. If another user approaches an already partially lit luminaire, the reaction depends on the direction they are coming from. If it is from the same direction as the previous user, no change is triggered in the system, and the luminaire remains illuminated. If it is coming from the opposite direction, then the third part of the luminaire that has so far been inactive is lit. As soon as the user passes the luminaire, the parts of the luminaire that are not necessary to ensure proper lighting conditions for other users are deactivated.

Figure 4. Areas of the road surface illuminated by the individual luminaire sections.
4. Discussion

The lighting system presented here is most easily compared to the standard concurrent lighting system in which the luminous flux of the entire luminaire is regulated. Using the measurement data on traffic and energy consumption from Bożeny Street in Poznań, Poland, an analysis was made of how a system using three-zone luminaires would work in this location. Due to the fact that in this location, at night there is practically no simultaneous traffic in both directions (in the evening and at night there is traffic in the direction towards the housing estate, while in the morning there is traffic out of the housing estate), only two out of the three luminaire zones always switch on. The use of a concurrent lighting system in this location, controlling the entire luminaires, gave a reduction in the energy consumption of 87% compared to a continuous operation at full power [8]. Compared to this system, the advanced system allows a 33% reduction in electricity consumption without compromising the quality of vision for users, that is, a 91% reduction in the energy consumed by the lighting system when operating at full rated power continuously.

The level of reduction in electricity consumption, as in standard concurrent lighting systems, depends on the level of traffic volume and its fluctuation during the lighting operating time, as well as on the baseline and the reduced roadway illumination levels. The greater the reduction in late-night traffic and the greater the reduction in the luminaire illumination during times when there are no users on the road, the more significant the economic effects. Each case of using a concurrent system with three-zone luminaires, as in the standard version, should be calculated individually, and the sense of its use should be assessed.

Detailed analyses of energy effects resulting from the use of concurrent lighting systems were described in an earlier publication [14]. The use of three-zone luminaires, except in the case described below, makes sense only where a conventional system of concurrent lighting controlling the entire luminaires will work properly. Compared to this system, full use of the possibilities of three-zone luminaires will give savings of up to 33%. Such saving occurs in the most favorable case of lighting, when the road surface shows higher gloss, e.g., such as asphalt (pavement type R3). In the case of less shiny surfaces, such as concrete or in the case of roads with wide roadsides, which must be well lit regardless of the direction from which the vehicle is approaching, lower savings due to the use of a three-zone luminaire can be expected.

Luminaires with independent control of the three lighting zones may also be used to reduce electricity consumption in permanent lighting systems. For example, they may be used to illuminate dual carriageways with divided traffic directions or one-way roads. In
such a situation, there will be two parts working continuously: the central part and the left or right part, respectively, to the arrangement of the luminaires. The inactive part in typical operating conditions may be activated depending on the need, for example, in the case of an emergency need to move traffic in both directions on one of the carriageways or the necessity of unblocking the traffic flow. In such cases, the use of three-zone luminaires allows reducing energy consumption by 33%.

5. Conclusions

Using the solution of the controlled luminaire with three independent sections described here, it is important to meet the lighting needs of all road users. To calculate the exact value of the energy savings in each case, detailed calculations should be made, and a dedicated luminaire should be designed. The luminaire currently requires implementation into the production and field testing in actual lighting installations. The luminaire must be properly designed in accordance with the modern art of high-performance lighting and optical systems design and also appropriately controlled. The system should be tested and adjusted for proper control before it is implemented. The system must take into account emergency situations, and if there is such a possibility, it is acceptable to change the type of the user, e.g., parking the vehicle with the driver or passenger going further on foot or a pedestrian entering a parked vehicle. When designing the system, one should not forget about such unusual situations as turning back.

The next stage of work might be an attempt to reconcile the operation of a concurrent lighting system using three-zone luminaires with a system of luminaire dimming during the period of reduced traffic intensity late at night. However, taking into account the expected and practically achieved energy savings observed in conventional concurrent lighting systems, such a solution seems to contradict the idea of introducing concurrent lighting to ensure equal and high satisfaction of the lighting needs of road users, without discrimination of any group, depending on the time of day and night when they use the road.

6. Patents

This solution is protected by patent application no P.439181, filed at the Patent Office of the Republic of Poland.

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