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The concept of LED road lighting concurrent with vehicles

Abstract. *In this paper the concept of road lighting concurrent with vehicles based on light emitting diodes was introduced. The way of operating of the road lighting concurrent with vehicles system was characterised, as well as the limitation and potential benefits arising from the system using were indicated. The theoretical examples illustrating the operation of the system were also presented.*

Streszczenie. *W artykule przedstawiono autorską koncepcję oświetlenia dróg współbieżnego z pojazdami z wykorzystaniem diod elektroluminescencyjnych. Scharakteryzowano sposób funkcjonowania systemu współbieżnego oświetlenia dróg, wskazano ograniczenia i potencjalne korzyści wynikające z jego zastosowania. Zaprezentowano także teoretyczne przykłady ilustrujące funkcjonowanie proponowanego systemu (**Koncepcja oświetlenia dróg współbieżnego z pojazdami z wykorzystaniem diod elektroluminescencyjnych**).*

Keywords: road lighting, lighting control, light emitting diodes.
Słowa kluczowe: oświetlenie drogowe, sterowanie oświetlenia, diody elektroluminescencyjne.

Introduction

Nowadays, in nearly all human activities the energy efficient solutions have been considered. These activities arise from the fossil fuels price increase, influencing the electric energy price, as well as the natural environment concern. Most of well known technologies are analysed and improved taking into account the reduction of energy demand. The development of new, promising technologies is supported. Solutions that have been ineffective or impracticable so far are introducing today. The old ideas, that haven't been used so far, are linked with the new technologies, giving promising results. In that way, LED technology inspired the former idea of dynamic road lighting.

At the end of the 1980's, in Japan, the system of vehicle traffic monitoring was introduced and as a consequence the road lighting control idea appeared [1]. The idea hasn't been used in practise because there wasn't a suitable light source linking the quick reaction time (typical for incandescent lamps) and high luminous efficacy (typical for discharge lamps). The LED technology has opened the way to accomplish the nearly forgotten idea.

System idea

The ground of the road lighting concurrent with vehicles results in the fundamental notion that the road lighting is not created just for the lighting purpose but for the safety and comfort of road users [2][3]. The user is the subject and the road is the object of lighting. For such statement the road lighting is not rational without the user. As a result, the road without the user shouldn't be illuminated – if no one observes a road, lighting can be switched off. However, because some unexpected users that can't be detected by the system, i.e. moving out of the main road, force the necessity for constant illumination at the minimum level, much lower than the required at the normal conditions [4].

The development in electronics, in the area of automatic data gathering, storing and analysing allows treating the lighting installation in a new way. The automatic systems of road lighting conditions and vehicle traffic monitoring have been created. The reasonable consequence of these opportunities is their linking.

For the last years LEDs have covered a long distance, starting from the luminous efficacy of the incandescent lamps achieving the level of the medium effective discharge lamps now. The primary, quick ignition and easy, full range luminous flux regulation is kept.

The dynamic lighting combines the electronic system of monitoring and controlling with high LED luminous efficacy in active energy conservation. The dynamic lighting system is the simplest way to save the energy and fulfil the lighting requirements on roads. The lighting is switched on when the users are on the road and is switched off when the users are not present. Moreover, the number of active luminaires depends on the needs. If the user needs the light from a luminaire to perform the task effectively, the luminaire is switched on. The performance of such lighting system shouldn't disturb or worry anyone. Its performance should conform to some rules.

A luminaire luminous flux is gradually increased some distance in front of a vehicle, operates until the cars are passing and, if no other vehicle is approaching, its luminous flux is gradually decreased and finally it is switched off. The length of the road in front of the vehicle that is illuminated depends on the speed limit first of all. It is adjusted to the maximum speed for a given road. Switching on and off are implemented gradually to achieve the impression of smoothness. Break time between subsequent illumination cycles shouldn't be shorter than some determined period, declared in the multiplicity of the illumination cycle length. If the distance between subsequent vehicles is too short to implement such break, the luminaire is not switched off until the distance is longer.

Settlement of such rules imposes on the system some limitations. Such system can't be implemented anywhere and anytime. Introducing of such system isn't economically proved when the traffic density at night doesn't drop to a low level for some time. Such system can't be implemented when the illuminated road is not long enough or there exists too many crossroads. Such system can't be implemented if many different users (i.e. vehicles, bikes and pedestrians) are present on the road and if in the near road environment buildings are present and light may cause anxiety for the residents. To implement the system, natural or artificial objects should exist between the road and buildings to reduce the negative lighting influence. Such objects can be: long distance itself, high or low greenery, aeroscreens or combination of the objects. It seems that lighting of nearby communication areas can fulfil such function either. When along the road a separate communication area exists (i.e. bike road or pavement) a separate lighting should be provided and included in the economic analysis. Counterindication for the system is also the traffic density increase in the near future that can be predicted.

The idea of the road lighting concurrent with vehicles is one of the ways in reducing electric energy and environmental impact, when quantitative and qualitative characteristics on the roads are achieved.

System assumptions

The aim of theoretical considerations, the study began with, is to elaborate the way the LED road lighting concurrent with vehicles is functioning at night, to evaluate levels of traffic density at which the use of the system is relevant and to demonstrate the potential savings resulting from the system use.

The works began with the hypothetical roads analysis. It was assumed that the considered roads were in built-up area and the speed limit was 50 km/h.

There is no opportunity to determine and analyse all theoretical luminaire layouts along the street. It is necessary to select one layout, which is representative at first, and to determine lighting conditions and control options for it. It would be good to select the layout with new lighting equipment that is the most often used now. In the beginning the layout with 30 m spacing was considered.

It was assumed that 1 km (or longer) road would be evaluated and all lighting parameters would be recalculated for 1 km road length. The single carriageway roads would be considered: with one- and two-way traffic. The dual carriageway roads would be treated as two single carriageways with one-way traffic on each. For each road single-sided arrangement would be analysed. Number of luminaires per 1 km, resulting from the above assumptions, was 34 and the spacing was 30,3 m. The considerations comprised variable traffic density: 10, 25, 50, 100 and 200 vehicles per hour in each direction. The assumed traffic densities exist in real conditions on Warsaw streets at night.

All analyses were conducted on model assuming uniform car distribution in time. This assumption didn't cause distortions as at a given traffic density two cars going in much shorter than average time results in break time extension between other vehicles.

Three systems of control cycles were considered: prompt – when at time, where vehicles are absent, is used to switch off the lamps, fast – where time of lamp switching off can't be shorter than the minimum lamp working time, and slow – where this time is two times longer. Introducing fast and slow cycles results from tendency that impression of chaos and irritation at potential observer can be caused by constant switching on and off.

The length of the road that should be illuminated in front of a vehicle should relate to the speed of this vehicle and the safe stop distance. At the assumed speed (50 km/h) in average atmospheric conditions on a typical road the length is shorter than 40 m. Due to the observation distance for calculation (measurement) field – 60 m according to standard PN-EN 13201:2003 [5] – the length of illuminated road shouldn't be shorter than 60 m plus extra two spacings. For roads with the higher speed limit the length of illuminated road should be relatively longer. Such length defines the number of the switched on luminaires at the same time. For the model road five on luminaires in front of a vehicle are assumed. In economic calculations the constant number of on luminaires is assumed. It is possible because when the next luminaire is at starting point (the process of increasing the luminous flux begins) the first luminaire behind a vehicle begins to switch off (the process of decreasing the luminous flux begins). Forcing the proper rate of luminous flux in time changes, the sum of powers of these two luminaires gives the power of one luminaire. The luminous flux increase (from zero to nominal value) and decrease (from nominal to zero value) is the same for each pair of luminaires and is pre-defined. It doesn't depend on the real vehicle speed.

When dynamics of lighting is planned the necessity of road sensoring should be taken into account. At any time the system should know the approximate, with one spacing accuracy, position, direction and speed of all vehicles on the road and near surroundings. Each luminaire should be equipped with detectors and data transmission net. Additionally, detectors of approaching vehicles should be installed. The initial area of the road as well as all crossroads should be illuminated permanently.

The system doesn't provide optical guidance. If such necessity should be provided, the condition of minimum luminous flux should be assumed to enable all the users visual guidance. In introductory analysis the total switching off was assumed.

System operation

The ground of the proper system operation forms the right detection of road users and determination of their movement. It requires using system of detectors that can correctly indicate presence of each vehicle, their movement direction and speed. From the achieved data the system must calculate momentary control parameters and indicate which luminaires should be switched on.

In front of each vehicle moving on road a light wave (near 100 m length along the road) should appear and it should move together with the vehicle. The next starting lamps should have ignition time regulated according to the speed limit on the road. The time of nominal luminous flux gain should be equal to the minimum time when the car is under the luminaire – the time at which the car with maximum speed limit covers the distance of one spacing. The same time of luminous flux reduction, for the luminaire the car passed, should be stated. In such a situation the car moving with the maximum speed limit will cause luminous flux smoothness of lamps switching on and off. Next luminaire that is switching on will start working when nearby luminaire gets the nominal luminous flux. Next car entering quicker the controlled road, at time shorter than the full working cycle (minimum off time), causes that the lamps don't off but wait for approaching vehicle.

The system off state behind the car should be analysed. Taking into account the fact that a vehicle can stop anytime, a luminous flux of passing luminaire begins to reduce in the moment the car passed the luminaire. Such action results in lengthen the time of luminaire operation and as a consequence decreases system profitability. Taking into account that the road in front of a car is illuminated mainly by the car lights, that the luminous flux is reduced gradually and that the influence of the passing luminaire on luminance is insignificant, it was assumed that the luminous flux of next luminaire (in correspondence to the passing luminaire) begins to reduce. Such an assumption will cause that the passed luminaire is just off. Both variants are possible but not optimal, the first because of higher cost and the second because of driver discomfort. As a final solution the reduction of the luminous flux begins when a car has just passed the luminaire and full off when the car is under the next luminaire – figure 1.

In case of dual carriageways independent operation on each carriageway is assumed. In case of single carriageway with two-way traffic a system should analyse the movement in each direction and include place and time of car lapsing, when driving opposite directions. Starting time of some luminaires in lapsing area should be lengthen to omit the situation of braking the light wave. In the fast system the number of working luminaires at the same time in lapsing area increases to $2n+1$, and in the slow system increases to $3n+1$; where n is the number of working luminaires, stated for a given road, for one passing car – figure 2.

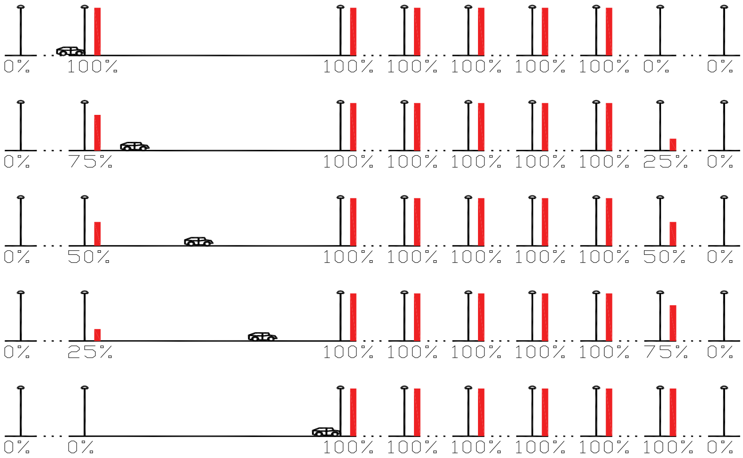

Fig. 1. The diagram of road lighting concurrent with vehicles.

Table 1. Luminaires operation time and energy reduction for one-way single carriageway illuminated by the concurrent system.

Car number per hour	Operation time of luminaires in initial section [s/h]	Operation time of luminaires In the controlled section [s/h]	Energy reduction on the whole road [%]	Energy reduction on the controlled section of road [%]
10	3600	131	82	96
25	3600	327	78	91
50	3600	655	70	82
100	3600	1309	54	64
200	3600	2618	23	27

Table 2. Luminaires operation time and energy reduction for two-way single carriageway illuminated by the concurrent system.

Car number for each way per hour	Operation time of luminaires in initial section [s/h]	Operation time of luminaires In the controlled section [s/h]	Energy reduction on the whole road [%]	Energy reduction on the controlled section of road [%]
10	3600	152	68	96
25	3600	462	62	87
50	3600	1191	47	67
100	3600	3456	3	4
200	3600	3600	0	0

A problem may arise when cars are entering the controlled section of the road. The controlled road section should be preceded with the initial section where lighting should be permanent. On this section car detection, determination of car speed and relative distances between cars are executed. The length of this section depends on the speed of the control system. In the prompt system the length equals at least *n* spacings, in the fast system double and in the slow system triple that length. Similar problem exists when traffic is introduced on the crossroads inside the active road. When a car appears on a transverse road luminaires on both sides must start as it isn't known where the car goes. The detection of driver intension would solve the problem more efficiently. A camera located over the crossroad would observe car approaching and capture the state of car dipped headlights identifying the driver action on the active road. According to the intention the suitable luminaires on the road section would be switched on.

The next issue that should be taken into account is the speed of vehicles. It is rare that cars are driving exactly with speed limit. Drivers often adjust speed for local conditions and drive slower or drive faster breaking rules. The system should adjust the speed of light wave to the real speed. In case of slower movement a lamp will wait to start working until a car appears. The section fully illuminated will be longer maximum by one spacing. In case of faster movement a lamp will start working before the previous one will get full luminous flux. At the speed 100% higher than the limit the section fully illuminated will be shorter by half of the spacing, but the number of working lamps doesn't change.

It is the common situation that there are two users on the road in the same time, moving the same direction but with different speeds, resulting in overtaking. The cars will be covered by separate light waves until the time between them will be longer than the cycle assumed. When they are closer, the light waves will join in one. The time of the common, longer wave will be decreasing when the cars are closer and closer reaching the standard length when the cars are in the same place on the road (overtaking point). After overtaking the light wave will be increasing until it separates into two independent light waves in front of each car.

Models of road lighting concurrent with vehicles

To illustrate the operation of the proposed, concurrent lighting system a few theoretical examples are presented.

The simplest case is the one-way traffic on a single carriageway. There is an initial section on the road, permanently illuminated by 5, 10 or 15 luminaires on the length of 120, 240 or 360 m respectively, depending on selected system. The setting of the other luminaires depends on the traffic conditions. When there are no cars on the road the luminaires are off. First luminaire will be on when approaching car is 150 m in front of it and will be off when the car passes it (unless the next car appears).

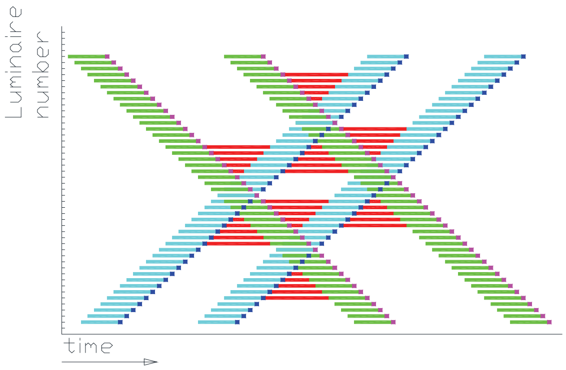

Fig. 2. The diagram of luminaire operation time on the two-way single carriageway road (cars driving opposite directions are passing) ; blue colour – the luminaires in front of cars driving up are operating; navy-blue colour – the position of cars driving up; green colour – the luminaires in front of cars driving down are operating; pink colour – the position of cars driving down; red colour – the luminaires in passing area are operating.

At the permanent permissible speed (50 km/h in this case) time of moving 1 km of the road is 72 s and time of moving one spacing is 2,18 s. The time of each lamp operation, when one car is driving, is 10,9 s then. The minimum time of the prompt cycle equals the time of lamp operation. In case of the fast cycle it is 21,8 s and in case of the slow cycle it is 32,7 s. The system will work when distances between cars are longer than 150, 270 and 390 m respectively. This results applied for traffic densities on the level of 330, 150 and 103 cars per hour respectively. The time operation per one hour for each luminaire was calculated as a function of passing cars – table 1.

The very common road situation is the two-way traffic on a single carriageway. As in any situation, the initial section is permanently illuminated. In this situation 5, 10 or 15 luminaires are on the initial section giving the length of 120, 240 or 360 m respectively, depending on selected system. The setting of the other 24 luminaires depends on the traffic conditions. Functioning of the controlled, active road is the same as in case of one-way traffic, except cars passing when driving in opposite directions. In the passing point 12 more luminaires are operating. The symmetry of traffic (the same number of cars driving in each direction) was assumed for calculations. For proper operation of the prompt system the traffic density in each direction should be half the density for one-way traffic and equals maximum 165 cars per hour in each direction. When the density is higher the lighting system operates constantly.

For constant, permissible speed (50 km/h) the time operation per one hour for each luminaire was determined as a function of passing cars – table 2.

Conclusions

The conducted analysis demonstrates that the proposed system can give substantial energy reduction on roads with low and very low traffic densities at night. Much better results are expected on dual carriageway when each road is treated as a separate one-way road. This corresponds to wide intersection between carriageways.

Further energy reduction is possible when road lighting concurrent with vehicles is applied but was not included in this paper. First, the quicker luminaire luminous flux reduction may be considered, before a car will pass it. It should be considered if it is necessary to illuminate 120 – 150 m of road, when the distance for safe stop is about 40 m. Further, if it is necessary to provide the minimum breaks in lamp operation as multiple (2, 3 times) of luminaire typical operation time or whether not to lengthen system operation time by introducing fractional break. Finally, the detailed analysis of car appearance distribution on road was not conducted and the influence of car grouping was not studied.

Hereto presented theoretical results should let begin to evaluate applicability of the system on given, real roads. Among the streets, where the control of traffic density is installed by the Municipal Road Administration in Warsaw, the roads where the density drops below boundary values will be selected. The 15 minutes analysis of car distribution will be conducted and real car appearance in time will be determined. The computer simulation of the system operation will be conducted and roads for prototype of concurrent lighting will be appointed. Information gathered from real lighting installation should be representative to take final decision about applicability of the system.

REFERENCES

[1] Yamada K., Honda T., Yamakawa K. *Road - Vehicle Lighting Integration -- A Study of the Phase I ROVELI System* The 3rd International Conference on Vehicle Navigation & Information Systems, IEEE, Oslo, 1992

[2] Boyce P. R., *Lighting for driving: roads, vehicles, signs and signals*, CRC Press, Taylor & Francis Group, London, 2009.

[3] Bommel W. J. M., Boer J. B., *Oświetlenie dróg*, WKŁ, Warszawa, 1984.

[4] Publikacja CIE 115-2010: *Lighting of roads for motor and pedestrian traffic,* CIE, Vienna, 2010.

[5] Norma PN-EN 13201-3:2007: *Oświetlenie dróg – Część 3: Obliczenia parametrów oświetleniowych*, PKN, Warszawa, 2007.

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