Light & Engineering
Vol. 28, No. 5, pp. 97–105, 2020

https://doi.org/10.33383/2019-107
Svetotekhnika #3, 2020, pp. 44–50

A NOVEL STRATEGY FOR TRANSFORMATION OF CONVENTIONAL ROAD LIGHTING TO SMART ROAD LIGHTING

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ABSTRACT

In recent years, smart road lighting (SRL) design and application researches has been increasing rapidly. However, SRL applications remain pilot project and cannot become widespread sufficiently. Main reason for this is that, although the cost of production of LED luminaires is reduced, when existing road lighting systems are transformed to LED road lighting, existing electrical installations and lighting poles cannot be used. Increased investment costs due to electrical installation and poles renovation, decrease interest in SRL transformation. In this study, an innovative solution is developed to decrease the costs of the SRL. First, a new LED luminaire is designed, which can work without changing the installations and poles of the existing projects. Then a test road is created using *DIALux* software, and the newly designed lighting installation is compared with completely redesigned one and conventional road lighting. Thus, contributions are provided for spreading of the SRL transformation, using low cost SRL approach.

Keywords: energy efficiency, LED luminaires, lighting, road lighting design, smart road lighting

1. INTRODUCTION

Nowadays, the communication possibilities of the devices increase with the developing technology. In this regard, many studies are performed and various concepts are developed. *Industry 4.0* is one of the concepts developed in this purpose. With the advent *Industry 4.0*, it has been possible to establish a faster network of objects, referred to as the Internet of Things, in which physical objects are coordinated with each other or larger systems [1]. Thus, objects that were formerly controlled by humans can now interact with each other through software and hardware mechanisms, such as algorithms, artificial intelligence, and wireless communication. In addition, they decide how the system works.

Variables that people may overlook due to carelessness are efficiently considered because there are no people in the decision-making mechanism of the Internet of Things [2]. All these technological developments have been utilized also in road lighting. In SRL systems, cameras and sensors measure external variables. The measured results are processed using algorithms to produce the desired data [3]. The data is transmitted to the network via wireless communication. The control mechanism is created by processing the data in the central control units. Thus, SRL systems are created that do not require human intervention, and efficiency is increased significantly.

In order to transform existing conventional road lighting systems to the SRL, it is necessary to add sensors to the existing system and establish communication networks, as well as to replace existing luminaires with controllable luminaires. High-pressure sodium (HPS) lamps used in conventional road lighting are difficult to dim, and the dimming steps are low. The lifetime of HPS lamps is shortened by frequent luminance changes. The closing and opening times are also long. LED luminaires have short dimming time, easy and precise luminance adjustment. The lifetime of the LED luminaires does not change with frequent changes of luminance. The closing and opening times are very short [4]. LED luminaires also produce less harmonics than luminaires with HPS lamps [5]. Thanks to this information, LEDs are preferred instead of HPS lamps in the SRL.

Conventional road lighting systems do not provide appropriate lighting for changing situations [6]. Many important parameters for road lighting, such as traffic flow and vehicle speed change momentarily. Thus, driver safety, driving comfort and energy efficiency of the system are not ideal. Well-designed road lighting saves energy, time, labour and costs [7]. The investment costs are high due to the additional equipment needed for the SRL [8]. Another important factor that increases the investment costs is need to change the distance between poles and their length in the existing road lighting, because LED luminaires to be used instead of luminaires with HPS lamps cannot efficiently provide lighting in this conditions. When changing the distance between poles in road lighting, all electrical installations must be replaced. Furthermore, if the height of the pole is changed, new poles must be used. This situation significantly increases the cost of the SRL. Therefore, it is difficult to expect that the SRL will become widespread and preferred by decision makers, especially in developing countries like Turkey, where investments are made with limited resources. In contrast to increased investment costs, operating costs are expected to be decreased due to the high energy efficiency of the SRL. Two important parameters affect energy efficiency in the SRL. First, it is the use of LEDs instead of HPS lamps. LEDs have a much higher efficiency factor than HPS lamps used in conventional road lighting, so their energy consumption is considerably low. Secondly, when using LED luminaires in the SRL, sensitive dimming can be made. Another positive effect of this is reduction of CO_2 emissions. In a study performed in Saudi Arabia, it was observed that the CO_2 emissions were 900 % higher with the use of petroleum and petroleum products instead of renewable energy in the production of consumed energy for lighting [9].

When considering the benefits such as reduced energy consumption and CO_2 emissions, as well as improved driver comfort, the SRL is needed to be expanded rapidly. In this study, cost reducing solutions are proposed to accelerate the process of transformation to the SRL. Smart road lighting is created by replacing the luminaires with HPS lamps to LED luminaires without changing existing electrical installation and lighting poles. This reduces the cost of installation. In this respect, an appropriate LED luminaire is designed to be installed on existing poles. The relationship between the lighting pole geometries and the light distribution curves of the designed luminaires is examined. A test road is created in *DIALux* software, and the developed solutions are examined in the test road. The proposed solution is compared with the conventional road lighting and the situation that the whole system is renewed.

2. SMART ROAD LIGHTING

There are two important criteria in designing the SRL. The first is that road lighting conforms to guidelines and standards accepted and used around the world. The second is to enable the hardware in the road lighting installation to interact with each other. This study examines the guidelines used by International Commission on Illumination (CIE) and *Zigbee* wireless communication protocol for the design of road lighting project [10, 11].

In international standards and guidelines, the most important criteria for the SRL is luminance. Luminance is a measure of how bright a surface looks. The technical report CIE140–2000 describes in detail all the necessary parameters to achieve appropriate luminance [10]. In cases where the road lighting classes are changed due to dimming, these parameters must be adjusted appropriately for each road class. In this study, investigations are performed between *M*1 and *M*5 road classes, and all of these parameters are considered to achieve successful road lighting.

In addition, wireless communication is one of the most important elements of the SRL. Thanks to the wireless communication, the system becomes manageable from a single point. In this way, by putting the control in one place, controls made by people can be fully autonomous with a good algorithm. Thus, many variables can be calculated for very complex road lighting and dynamic, efficient lighting can be provided.

The SRL uses *Zigbee* wireless communication network. A fast and simple network structure can be established with *Zigbee* [11].The *Zigbee* protocol communicates with radio waves. Radio waves prop-

Table 1. Technical Data of Luminaires and Poles in Scenarios

	Classical road lighting	Only luminaires are replaced	Completely redesigned system
Power of luminaire	447 W	305 W	243 W
Luminous flux of luminaire	45866 lm	45192 lm	28862 lm
Pole heights	14 m	14 m	10 m
Pole distance	40 m	40 m	35 m
Pole numbers	25 pc.	25 pc.	29 pc.
Pole boom lengths	2.5 m	2.5 m	3 m
Pole boom angles	0˚	0˚	0˚
Arrangement type	Single row from the right	Single row from the right	Single row from the right

agate in the space at the speed of light. The speed of the radio waves should be considered, as it will cause a delay in calculating the speed of the vehicles that pass on the road.

3. CASE STUDY

When making the roads smart, that is actually to answer the questions:

– How the topology of the network will be;

– How the system will follow a strategy in case of a possible failure;

– How dynamic lighting of the roads will have an impact on the drivers.

Before doing this, it should be analysed using questionnaires and tests to make a decision about optimum design. In this study, a test road is created in the computer environment to determine why it is necessary to get road lighting smart and which method of transforming the SRL is more appropriate.

3.1. Creating the Test Road

In this part of the study, a test road is created according to the LED lighting regulation prepared by *Turkish Electricity Distribution Corporation (TEDAŞ)* [12]. The test road has three lanes, each lane is 3.5 m wide and the test road is 1000 m long. When positioning poles along the test road, the first pole is positioned at half the selected pole distance from the starting point. Accordingly, the number of poles is determined.

The test road is created according to three different scenarios. The first is the conventional road lighting. In the second scenario, only luminaires with HPS lamps in conventional road lighting are replaced with LED luminaires. In this case, only the luminaires are modified and other parameters, such as pole distance and pole heights are the same as conventional road lighting. In the third scenario, all the electrical instalments such as pole distance, pole heights, luminaires etc. are designed from the beginning by changing all these parameters. Thus, the SRL is created. The details of designs for these three scenarios are shown in Table 1.

In the third scenario, the parameters are selected in order to minimize energy consumption. Thus, each scenario can be compared with high accuracy, considering energy efficiency. In all scenarios, lighting classes are designed to ensure luminance values between *M*1 and *M*5 road lighting classes, according to varying traffic intensities.

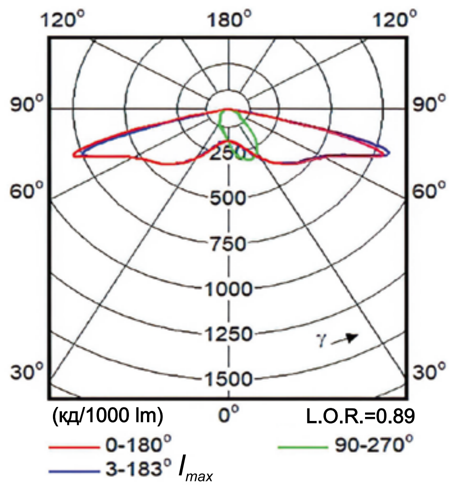

Fig. 1. The distribution curve of luminous intensity of the LED luminaire used in the second scenario

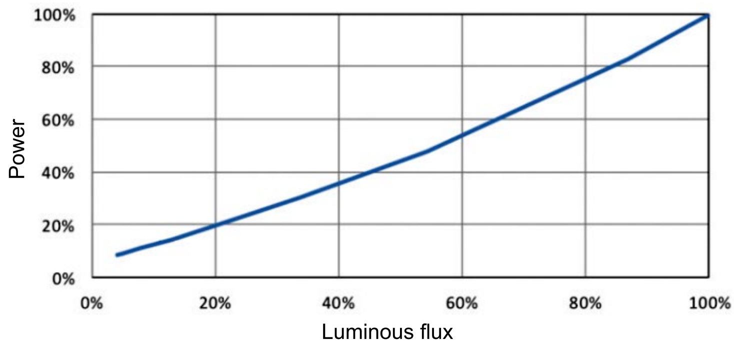

Fig. 2. LED luminaire dimming example relative luminous flux vs power [13]

3.2. Investigation of the Effect of Pole Geometry

Pole geometries are very important in road lighting. The lighting pole geometry and luminaire distribution curve of luminous intensity directly affect each other. In order to obtain a good lighting design, either the pole geometry should be determined according to selected luminaire geometry, or a suitable luminaire should be chosen according to the specific pole geometry.

The distribution curves of luminous intensity published by many manufacturers were examined for luminaires with HPS lamps used in conventional road lighting. As a result of the examinations, it was observed that distribution curve of luminous intensity *C* and γ planes of luminaires with HPS lamps have a circular shape. In LED luminaires, the distribution curves of luminous intensity have no specific shape. Thanks to the arrangement of the lenses and LED luminaires, the distribution curves of luminous intensity can be changed. However, as the height of the pole increases in the road lighting, the distribution curves of luminous intensity should be extended horizontally in parallel with the road using the *C* and γ planes for uniform light distribution. Fig. 1 shows the distribution curves of luminous intensity of the LED luminaire used in the second scenario.

Since existing pole distance used in the study are longer than normal for LED luminaires, the distribution curves of luminous intensity is determined horizontally in parallel with the road. Pole geometry depends on pole height, boom lengths of poles, boom angle of poles and pole-road distance. The dependence between pole geometry and distribution curves of luminous intensity is examined for luminaires with HPS lamps in *DIALux*. If the height of the pole is 14 m, and the pole-road distance is taken as 0.5 m, then the examination is considered sufficient in three cases:

– Assuming the boom angle of poles is 0°, increasing the boom lengths of poles by 0.1 m;

– Assuming the boom lengths of poles is 2.5 m, increasing the boom angle of poles by 0.1°;

– Increasing the boom angle of poles and the boom lengths of poles by different combinations.

According to these three cases, it is observed that the average pole geometry should be either the boom lengths of poles of (3.5 – 6) m and the boom angle of poles of (0° – 10°) or the boom lengths of poles of (2.5 – 3.5) m and the boom angle of poles of (5° – 15°).

Since LED luminaires do not have specific distribution curves of luminous intensity, a standard pole geometry could not be found for LED luminaires in the examinations performed with *DIALux*. Therefore, when designing a SRL project, a suitable LED luminaire can be selected by referring to the pole geometry used in the projects. Thus, replacing existing luminaires with LED luminaires simultaneously ensures appropriate illumination and makes the system smart without changing the pole geometry of conventional road lighting.

3.3. Control Strategy and Luminaire Structure for Smart Road Lighting

The change in dimming-related energy consumption of LED luminaires for the SRL has an approximate linear relation. Fig. 2 shows this relation. Therefore, the study assumes that LED luminaires consume energy in a linearly changing manner by dimming.

Sensors and communication modules must be installed in luminaires to make the road lighting smart by changing luminaires without changing the existing pole structure. Thus, the luminaires can transfer variable traffic and weather conditions from the real environment to the virtual environment. In this study, a luminaire, which is currently used in con-

Table 2. The Average Monthly Sunset and Sunrise Hours in Istanbul and Total Operating Time of a Luminaire [14]

Months	Jan.	Feb.	Mar.	Apr.	May	Jun.
Average sunset and sunrise hours	18:01	18:37	19:08	19:44	20:15	20:37
	–	–	–	–	–	–
	08:25	07:58	07:19	06:25	05:46	05:32
Total operating time of a luminaire (h)	446.4	373.8	377.68	320.5	295.02	267.5
Months	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Average sunset and sunrise hours	20:33	20:00	19:12	18:25	17:46	17:38
	–	–	–	–	–	–
	05:46	06:14	06:44	07:15	07:51	08:21
Total operating time of a luminaire (h)	285.7	317.23	346	397.83	422.5	456.22

ventional lighting, is redesigned without changing its pole structure for the second scenario. In order to get rid of the cables inside the luminaire, use an equipment that has a socket and can be fixed to the outer cover of the luminaire. The communication module, the sensor module, the driver and the LED luminaire each have a slot. In this way, it is expected to reduce solution time and labour costs in case of hardware failures of the luminaire. Fig. 3 shows bottom view, top view, and side view of the luminaire in a millimetre scale.

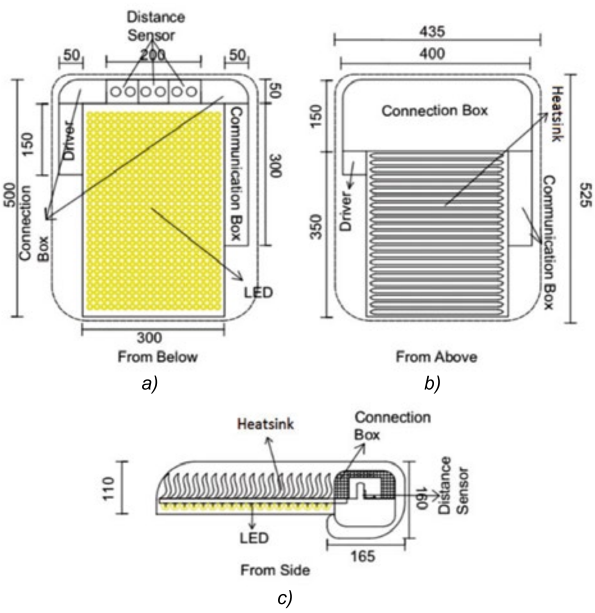

Fig. 3. Demonstrations of the designed luminaire: bottom view (a), top view (b), side view (c)

Determining vehicle speed and traffic intensity in the SRL system is critical. This information is used for dimming LED luminaires, thus very high-energy efficiency levels can be achieved compared to conventional lighting. The SRL system tracks vehicles using height information of vehicles. In Fig. 4, distances between luminaires and the test road lane are shown in meter scale while a vehicle not passing, and while a vehicle passing.

The luminaires are equipped with laser distance measuring sensors. These sensors recalculate the speed of the vehicle at each pole it passes. Therefore, the control system identifies the vehicle by matching the height information of the vehicle with the luminaires it passes through. The traffic flow is determined by the number of vehicles passing in front of a pole during a determined period according to vehicle speed. The speed of a vehicle is determined by the time it takes to cross the poles. The

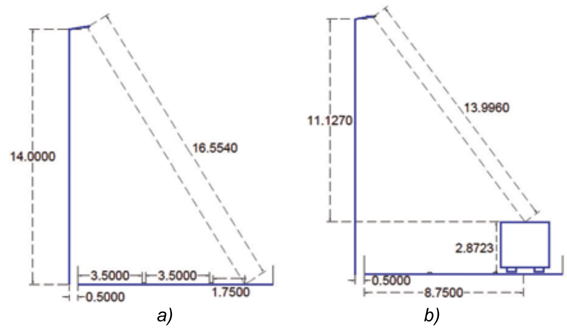

Fig. 4. The distance between the luminaire and the test road when the vehicle does not pass (a) and the vehicle passes (b)

Table 3. Annual Energy Consumption and Achieved Energy Saving For Each Scenario

Relative luminous flux of luminaires	100 %	75 %	50 %	25 %	Total	Energy saving (E_s^i)
1. Conventional road lighting	4306.4 h 48124 kW·h	–	–	–	4306.4 h 48124 kW·h	Reference
2.1. Only luminaires are replaced, without dimming	4306.4 h 32836 kW·h	–	–	–	4306.4 h 32836 kW·h	31.77 %
2.2. Only luminaires are replaced, with dimming	66.43 h 2454.26 kW·h	324 h 1920.47 kWh	1389.43 h 5595.68 kW·h	2526.53 h 4174.68 kW·h	4306.4 h 12472.85 kW·h	74.08 %
3. Completely redesigned system	66.43 h 2204.79 kW·h	324 h 1774.89 kWh	1389.43 h 5171.44 kW·h	2526.53 h 3858.23 kW·h	4306.4 h 1157.37 kW·h	76.04 %

speed of a vehicle is calculated as follows: when the vehicle has crossed a certain pole, the next pole receives the signal, which is the vehicle is coming, with a specific delay, and the time that takes to reach the next pole is measured with this delay. The time it takes for the radio wave that locate in Eq. 1 to cross the same pole is calculated. Then these two calculated times are added up. Thus, the speed of the vehicle is determined by dividing the distance by the time obtained.

3.4. Comparison of Different Scenarios

This part of the study provides a one-year energy consumption analyses for designed three scenarios on the test road created in computer environment. In the analyses, firstly operating time of luminaires are determined by considering the average monthly time of sunset and sunrise in Istanbul. Table 2 shows the average monthly sunset and sunrise times in Istanbul and the total operating time of a luminaire.

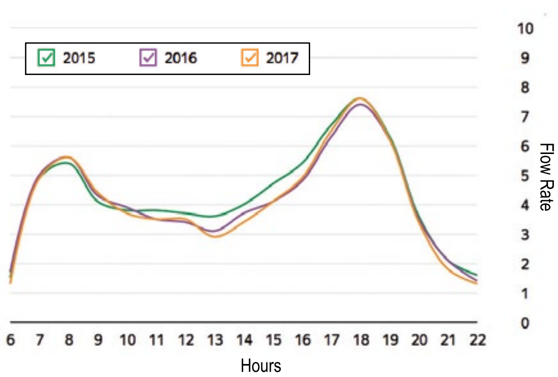

Fig. 5. Hourly traffic flow in Istanbul [15]

After determining operating time of luminaires on a monthly basis, as one of the basic principles of the SRL, it should be decided to what extent the luminaires are dimmed according to condition of the road. Thus, continuous monitoring of the road with the help of sensors should ensure the appropriate dimming. For this purpose according to the CIE recommendations, road dimming rates should be determined by selecting class of the road according to structure of the road, flow, and speed of vehicles. Accordingly, real traffic flow data of in Istanbul is used to determine these dimming rates. Fig. 5 shows hourly traffic flow in Istanbul.

In this study, to compare scenarios with each other, luminous flux of the luminaire depending on dimming rates is determined according to the actual traffic flow data obtained from Fig. 5 in Istanbul in accordance with regulations. Fig. 6 shows determined relative luminous flux of the luminaire according time intervals in a day.

When Fig. 6 is examined, it is observed that the relative luminous flux is coherent with hourly traffic flow in İstanbul shown in Fig. 5. When the traffic flow falls below 10 %, luminous flux of the luminaire is kept at 25 % for safety reasons. In the calculations, instantaneous luminous flux changes are not considered due to the lack of data. In this study, 2.6 cd/m^2 is chosen for $M1$ road class instead of 2 cd/m^2, which is the lower limit for luminance level. Because to make an appropriate comparison between smart and conventional road lighting. In

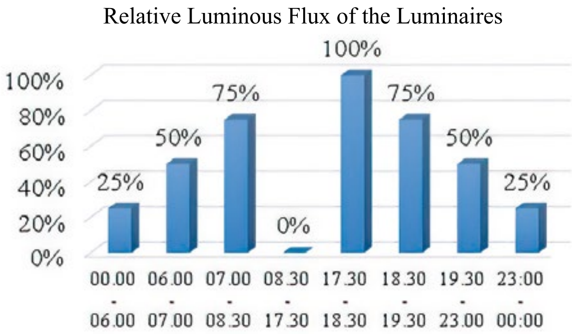

Fig. 6. Relative luminous flux of luminaires in Istanbul (luminaires do not active during the daytime)

addition, luminance levels are preferred above the minimum luminance level, considering the maintenance factor of the luminaires. According to the relative luminous flux in Fig. 6, 100 %, 75 %, 50 %, 25 % luminous fluxes correspond to the luminance values of road lighting classes *M*1, *M*2, *M*3, and *M*5, respectively. After determining the luminous flux of the luminaires depending on hours, in order to find total energy consumption, it is determined by how long the luminaires work in case at each luminous flux level considering the average time of sunset and sunrise in Istanbul. In Fig. 7, the operating time of the luminaires at variable luminous flux levels is set monthly.

Using Fig. 7, annual operating times of luminous flux levels for each scenario are calculated. Then, the annual energy consumption and energy saving for each scenario are calculated as follows:

$$P_t^{i,j} = P_l^i \cdot P_r^{i,j} \cdot NP^i, \quad (1)$$

$$E_y^{i,j} = P_t^{i,j} \cdot OT^{i,j}, \quad (2)$$

$$E_y^i = \sum_{j \in \mathcal{J}^i} E_y^{i,j}, \quad (3)$$

where $P_t^{i,j}$ is total power of the system, P_l^i is power of a luminaire, $P_r^{i,j} \in \{0.25, 0.5, 0.75, 1\}$ is power ratio dependent on variable luminous flux, NP^i is number of pole, $E_y^{i,j}$ is yearly total energy consumption, $OT^{i,j}$ is operating time, $\mathcal{I} = \{1, 2.1, 2.2, 3\}$ is the set of scenarios, $i \in \mathcal{I}$ is the scenario number, $\mathcal{I}^i$ is the set of luminous flux levels for scenario i, and $j \in \mathcal{J}^i$ is the luminous flux level. The data associated with these variables are given in the relevant sections of Table 1, Fig. 6, and Fig. 7.

Conventional road lighting is chosen as reference to achieve the energy saving in the other scenarios. The energy savings relative to conventional road lighting (E_s^i) are calculated as follows:

$$E_s^i = \frac{E_y^1 - E_y^i}{E_y^1} \cdot 100\,. \quad (4)$$

After the calculations, the annual energy consumption and achieved energy saving for each scenario are shown in Table 3, together with operating times of luminaires at different luminous flux level.

Energy consumption is high in conventional road lighting, since dimming is not performed and HPS lamps are used. The scenario 2, where only the luminaires are replaced without changing the electrical installation and poles, is examined in two different cases to determine the energy savings achieved by dimming and changing HPS lamps with LEDs, respectively. The achieved energy savings in the first case is 31.77 % due to the replacement HPS lamps with LEDs without dimming. In the second case, energy saving is 74.08 % with dimming. So in case of dimming, the energy savings are highly increased. However, the cost increases slightly com-

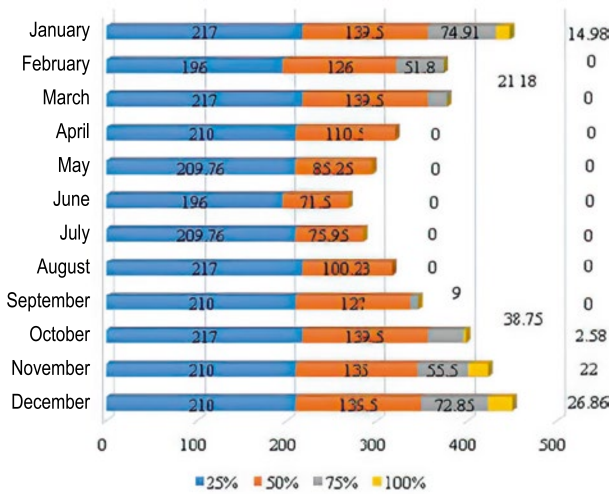

Fig. 7. Monthly operating time of the luminaire at variable luminous flux levels

pared to the first case due to equipment required for dimming. In the third scenario, which is the case where poles, electrical installations and luminaires are completely replaced to achieve maximum energy savings, the energy savings are 76.04 %. When the results are examined, it is observed that obtained energy saving only by replacing the luminaires is very close to the one achieved by replacing the whole system.

4. CONCLUSIONS

High costs lead to the fact that the SRL cannot be widespread. In this study, an appropriate LED luminaire is designed and the SRL transformation is proposed without changing the electrical installation and poles. It is observed that the SRL created only by replacing the luminaires provides very high energy saving. Even if it is found that the scenario of changing the whole structure is the highest energy saving scenario, in this case the investment cost is quite high. In the proposed solution, high costs are reduced, since only the luminaires are replaced. Thus, it is shown that the SRL can be performed with low costs. Reducing high costs will make a significant contribution to spread of the SRL, especially in developing countries where the SRL cannot become widespread.

In this study, the costs of the scenarios are not examined in detail due to the lack of data. However, if a cost comparison is performed, it would already appear that proposed solution has a relatively low cost compared to the third scenario, since the proposed solution does not replace the poles and electrical installations. When the proposed solution is compared with conventional road lighting, only the luminaires are replaced. This cost can be paid back in a short time with the high energy saving.

Nevertheless, it will be more useful for decision makers to determine the break-even time of the options with detailed cost/benefit analyses using the net present value method.

In addition, changing the road class by dimming for energy saving can cause safety problems. In fact, for the *M*1 road class, the luminance level is allowed to reduce to maximum of *M*3 road class. In this study, when no vehicle passes, the luminance level is reduced to *M*5 road class. For safety reasons, the luminaires are not turn off completely. If a vehicle passes through the road, sensors detect this vehicle, and the luminance level at the location where the vehicle passes is increased to *M*3 road class. In countries with high acceptable level of risk and difficulties in energy supply, it may be an appropriate option to reduce the luminance level to the *M*5 road class.

In this study, only technical analysis of the SRL is performed. Thus, potential energy savings of the SRLs are shown. However, it is up to the decision makers to determine the luminance level of road class by considering the energy saving and safety criteria.

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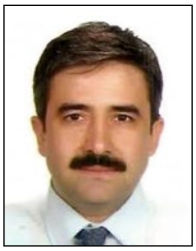

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