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Influence of the lighting surface and luminance of the brake lamp on the observation comfort

***Abstract:** This article presents the results of stop lamp visibility analysis. The lamp was especially designed to enable changing of the luminance and lightning surface. The research were carried out on the group of the observers for three various lighting conditions and a few luminance and lighting surface combinations. The results shows that change of the lighting surface combined with luminance change allows to significantly increase readability of the visual signs and improve observation comfort as well.*

Streszczenie:** W pracy podjęto problem oceny postrzegania światła hamowania, która pozwala uwzględnić oprócz światłości także luminancję i powierzchnię świetlną klosza. Urządzenie zostało wykorzystane do przeprowadzenia badania ankietowego na grupie obserwatorów. Na podstawie uzyskanych wyników stwierdzono, że optymalne postrzeganie światła hamowania w różnych warunkach obserwacji zależy nie tylko od światłości, ale także od luminancji i powierzchni świetlnej klosza. (**Wpływ wartości luminancji i pola powierzchni świetlnej klosza światła hamowania na widoczność sygnałów świetlnych)

Słowa kluczowe: lampy hamowania, olśnienie, lampy sygnalizacyjne, optymalne postrzeganie światła.
Keywords: stop lamps, glare, signaling lamps, visual comfort

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Introduction

Light signal reaching the observer has the following features that uniquely identify it [1]: luminous intensity (luminance), color, shape (contour), angular size, position in the field of view of the observer, and the characteristic way of emission (timing, coding).

These six characteristics of the light signal means also that each of them alone can decide on the distinguishability of the signal. If we speak about two light signals in some signaling system (eg, braking and positional signal of a vehicle) it is enough for them to differ with at least one feature and this will ensure the correct interpretation of each signal. But in the case of safety-relevant signals at least two different characteristics are used, in order to minimize the likelihood of misinterpretation of the message. In the case of the vehicle signal lights the different colors (white, car-yellow, red), different levels of luminous intensity (such as rear position lights and stop lights) and time coding (intermittent light signal of the direction of travel) are used.

Rear position and stop lights [2] are red, and until recently differed in only one feature (luminous intensity). Since the introduction of the stop lights of S3 category, ie. the third stop light, the second feature has appeared, which allows reliable differentiation of braking and positional signals eg., the location in the field of view of an observer. But the problem of the optimal lamp luminous intensity, which results from the necessity of clear differentiation of the position and stop lights, still remains. Position lights must be visible at night, while in the day when the silhouette of the vehicle is clearly visible, it is not important from a safety standpoint. The stop light must have greater luminous intensity than the position light so that the braking maneuver is clearly visible in all outdoor conditions. Selecting the right luminous intensity is very difficult, because the stop lights must be:

- clearly distinguishable from the rear position light,
- clearly visible during the day with extremely strong sunlight,
- does not cause glare at night when vision is adapted to lower light levels (mesopic vision).

In the last few years, application of the various signals color is also considered as a way to improve the distinguishability of the stop lamp signal [3,4]

In 2007, the Regulations of the United Nations Economic Commission for Europe (UNECE) [5] introduced the possibility of a smooth change of luminous intensity, of course, within the obligatory ranges of luminous intensities. This allows to optimize the lamp performance to a large extent, in order to ensure the best perception of light signals. Still unsettled is the question of the relative proportions of the lighting surface area and luminance of the lens, which are decisive for the luminous intensity of the lamp. In result the same value of luminous intensity can be obtained with different combinations of luminance and size of the lighting surface. To simplify the considerations, and using the average value of the luminance instead of luminance distribution, it is worth noting that the luminous intensity I can be the result of different combinations of the product of the apparent surface area s_i and its luminance L_i.

$$I_0 = s_1 L_1 = s_2 L_2 = ... = s_i L_i \tag{1}$$

Thus, the signal of the threshold luminous intensity I_o can be realized by a large area of low luminance as well as a small area of high luminance. For example, the signal with a threshold luminous intensity of 100 cd can be achieved by using several combinations of luminance and the apparent surface area, eg. 100 cd = 1 cm^2 ·10^6 cd/m^2 = 10 cm^2 ·10^5 cd/m^2 = 100 cm^2 ·10^4 cd/m^2 = etc.

As seen in the example, the same effect of producing at least the threshold luminous intensity I_o (the threshold light intensity, E_o) may be due to lighting of the signal lamp surfaces differing by two orders of magnitude of luminance.

For a light signal of small angular size, in the given conditions of visual adaptation, to be seen as a colored light stimulus, it must produce at least the threshold light intensity E_o on the pupil of the observer. The absolute value of that light intensity, for observations in the day, ranges from $2 \cdot 10^{-3} \div 2 \cdot 10^{-2}$lx. For night viewing conditions, this value is much lower and varies between $2 \cdot 10^{-7} \div 2 \cdot 10^{-5}$lx.

In the following paper it is proposed the method [6-9], which allows the assessment of the optimal visibility of the stop lights, which takes into account both the threshold light intensity and glare effects. The prepared lamp model using the Eq. (1) allows for almost any adjustment of the lighting surface and luminance of the lens.

Study of the luminance distribution of the stop lamp lens

The studies of environment luminance distribution were conducted using a matrix luminance meter [10,11]. Combinations of different types of external conditions are very numerous, because they are a complex of different hours of day, seasons of year, weather conditions, different levels of lighting with sunlight and artificial light, or even different color of the vehicle body. This analysis is to determine what background luminance values occur at selected external conditions. For the purposes of further analysis the following cases were selected:

a) daytime, winter, snow-covered shoulder (Figs. 1, 2),

b) daytime, summer, the vehicle directly illuminated by sunlight (Figs. 3, 4),

c) night time, summer, the vehicle illuminated by street lamps (Figs. 5, 6).

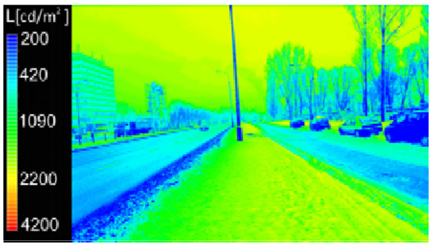

Fig. 1 Environment luminance distribution [cd/m^2]. daytime, winter, snow-covered road shoulder.

Fig. 2 Environment luminance distribution [cd/m^2]. daytime, winter, vehicle at the background of snow.

Fig. 3 Environment luminance distribution [cd/m^2]. daytime, summer, vehicle directly illuminated by the sun.

Fig. 4 Environment luminance distribution [cd/m^2]. daytime, summer, vehicle directly illuminated by the sun (changed range of luminance visualization).

Fig. 5 Environment luminance distribution [cd/m^2]. Nighttime, summer, vehicle illuminated with street lanterns.

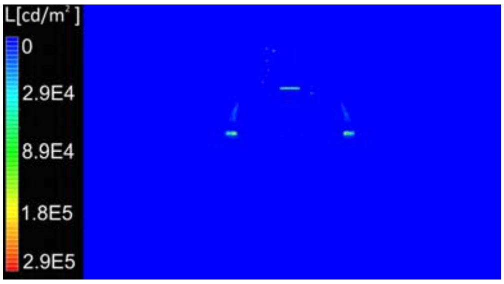

Fig. 6 Environment luminance distribution [cd/m^2]. Nighttime, summer, vehicle illuminated with street lanterns after switching on the stop lights.

Vision of the driver is subject to adaptation to ambient light levels. During the day the pupil shrinks, the sensitivity of the retina decreases too. At night, conversely, the pupil expands and the sensitivity of the retina increases up to the change in the nature of vision from photopic through mesopic up to scotopic. Thanks to this human is able to see well both at night and in a sunny day. The range of ambient luminance corresponding to a visual adaptation is very wide and ranges from fractions of cd/m^2 up to hundreds of thousands of cd/m^2. The key phenomenon for the perception of light signals is not fully explored. It is not known how the brightness of various parts of the observed image affects the level of vision adaptation, whether an eye adapts to the average value or the maximum one, whether specific parts of the retina have different impact on the level of adaptation. Additionally, also the individual characteristics of each of the observers must be taken into account, one shall remember that the photometric quantities, such as the spectral sensitivity curve of the human eye, is the average measured for a population of several thousand observers. The nature of visual adaptation is therefore the resultant of all these cases.

Under the analysis the values of the stop light luminance obtained from measurements were compared with the values of luminance characteristic for a given type of outdoor lighting conditions.

At the conditions a) the following components of the scene, on which the vehicle and signal lights are observed, can be distinguished:

- snow on roadsides, fields, sometimes on the street – $L_{śr}$ = 1-10 kcd/m^2,
- surface of the street - $L_{śr}$ = 0,5 kcd/m^2,
- sky - $L_{śr}$ = 2-10 kcd/m^2,
- rear of the vehicle against which we observe a light signal (light lacquer) - $L_{śr}$ = 2,5 kcd/m^2,
- the average luminance of the whole scene in Fig. 2 $L_{śr}$ = 8 kcd/m^2.

In case of winter conditions the luminance value of the stop lights is a bit larger than the luminance of the vehicle silhouette, on which light is observed, even under extremely unfavorable case (light lacquer of the vehicle, a very small lens luminance). Luminance occurring in the environment are less than 10 kcd/m^2 and should not cause a disturbance in the perception of light signals. Low levels of luminance are caused by a small amount of sunlight reaching the earth's surface, on Polish territory, in the winter. In addition, a typical phenomenon of Polish roads is a thin layer of slush and dust covering the snow around the roadway, which greatly reduces the reflection coefficient and thus the luminance in the area of the road. The unfavorable phenomenon can be also related to the chemical clearing of roads, namely a very fast contamination of lamp lens, reducing very much the amount of light emitted by the lamp.

At the conditions b) you can identify the following components of the scene, on which we observe the signal lights:

- surface of the street - $L_{śr}$ = 2 kcd/m^2,
- sky - $L_{śr}$ = 5-10 kcd/m^2,
- rear of the vehicle against which we observe a light signal (light lacquer) - $L_{śr}$ = 6,5 15 kcd/m^2, at the places where we observe a mirror reflection of sunlight from the body parts in the direction of the observer the luminance reaches 0,5 Mcd/m^2,
- the average luminance of the whole scene in Fig. 3 $L_{śr}$ = 5 kcd/m^2.

In summer, due to lower angle of incidence of solar radiation on the earth surface, the luminance of the characteristics areas around the vehicle have greater values. In particular, the luminance of the rear part of the vehicle increases. This can be seen in Fig. 4. In the case of a bus (white lacquer) the luminance reaches 15 kcd/m^2, and so is the greater value than in the case of the parts of stop lights. It may therefore be a situation in which the stop lights will not be noticed. Another problem that occurs at the direct illumination of a vehicle with sun light are mirror images, where the luminance reaches 0.5 Mcd/m^2. In this case, the effect of glare may occur, which impairs the perception of light signals.

At the conditions c) you can distinguish the following components of the scene on which we observe the signal lights:

- surface of the street - $L_{śr}$ = 0,5-5 cd/m^2,
- sky - $L_{śr}$ = below 1 cd/m^2,
- rear of the vehicle against which we observe a light signal (light lacquer) - $L_{śr}$ = below 1 cd/m^2, in the places where we observe a mirror reflection of lantern light from the body parts in the direction of the observer the luminance comes up to 100 cd/m^2,
- the average luminance of the whole scene in Fig. 3 $L_{śr}$ = 1 cd/m^2.

In the case of nighttime the luminance occurring in the vicinity of the vehicle are on the level of a few cd/m^2, and thus they are smaller by 2 - 3 orders of magnitude than the luminance of the stop lights. The driver does not have any problems with the perception of light signals, even with the small mirror reflections of the light from street lanterns. A major problem in these conditions is a glare phenomenon. At night the vision adapts to the level of a few - a few dozen of cd/m^2 and observation of stop lights can cause discomfort or even the glare occurrence. With this case we are dealing particularly at small distances of observation (slow driving, lights, traffic jams).

Control system of the lamp model

In the developed system of wireless control of a stop lamp the radio transmission within the band of 433 MHz with FSK/GFSK modulation was applied. The transmitting part (Fig. 7) includes: FPGA control module shaping the serial data transmission protocol of the transmitted signal, the transmitting modem converting the digital form of a signal into a high-frequency modulated signal with a power of 100 mW, the transmitter antenna and two power packs. The transmitter modem is coupled to the control module via RS-232 interface. This connection allows you to apply the microcomputer for the synthesis of the transmission protocol, rather than the prototype module with the FPGA system used in this case. The FPGA module was more flexible at the stage of research work relating to the choice of an appropriate method of transmission, when it was necessary to test several solutions of protocols and transmission modules.

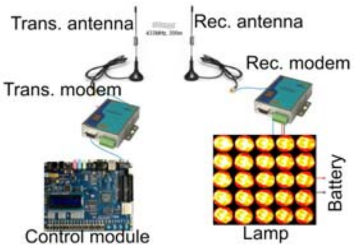

Fig. 7. Structure of the lamp control system

High-frequency modulated signal is received via an antenna by the receiver modem, which demodulates it into the digital form of the serial transmission protocol, which is identical with one shaped in the FPGA system on the transmitting side. The developed model of the reflector consists of three blocks: a matrix of LED (Light-Emitting Diode) containing 25 red LEDs connected in four sections, Mmfpga-12 module decoding the transmission protocol from the transmitting modem into 4 digital signals with variable frequency and the module forming the currents from these signals supplying individual sections of the LED matrix. The model of the reflector is supplied with 12V DC source such as a car battery. The supply voltage is converted by a set of converters to the voltages supplying the receiving modem, LED sections and other components of the reflector. Each LED section is capable of adjusting the supply current, which translates to the adjustment of the light stream value. At the condition of maximum control the reflector system collects a current of about 1.3 A from the power source.

Lamp module

The lamp module consists of three functional blocks: a matrix containing 25 red LEDs connected in four sections, MMfpga-12 module decoding the transmission protocol frame from the modem of the receiver to four digital signals with variable frequency and the module forming currents supplying the individual sections of the LED matrix.

The first section of the LED matrix (Fig. 8) contains four diodes connected in series and supplied from the anode side L1 with a voltage of 10 V, while from the cathode side L4 controlled with a constant current value, applied on the transmitting side, through the JP4 connector, pins 7-8, from the controller DD311 of the forming module. The second section is supplied with a voltage of 15V and has 5 LEDs, the third section contains seven LEDs supplied with a voltage of 15V and the fourth section is composed of 9 LEDs supplied with a voltage of 20V. The JP1 and JP3 connectors play an auxiliary role fixing the matrix. A view of one of the working versions of the LED matrix is shown in Fig 9.

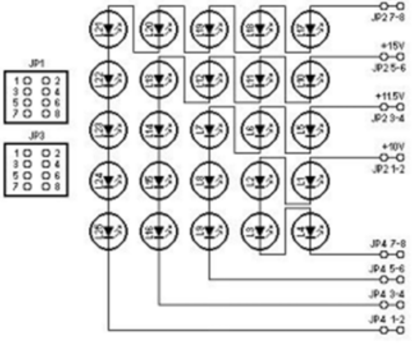

Fig. 8 Electrical diagram of the LED matrix

Fig. 9 The view of LED matrix

There is a forming module directly connected to the LED matrix, which is shown in Fig. 10. It contains the voltage converters supplying the individual sections of the LED matrix, Mmfpga-12 module, the set of switches for manual operation setting, integrated circuits of galvanic separation, voltage/frequency conversion and direct current amplification.

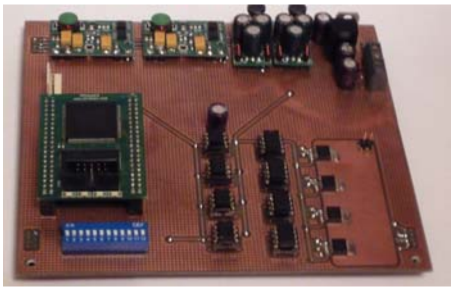

Fig. 10 The view of the lamp's electronic circuit

The study of visibility of lights

The research program of light visibility was developed based on the requirements of Reg. 7 UNECE. The stop lights were selected to tests because their correct perception and interpretation is essential for reasons of road safety. Other types of lights (position, clearance, reverse) are designed to facilitate observation of the silhouette of the vehicle on the road or have auxiliary functions, which is not a sudden phenomenon, requiring instant perception and quick response of the driver. In order to reduce the number of combinations of different luminance, lighting surfaces and types of lights also the examination of direction indicator lamps and position lamps integrated with the function of stop lights were given up. However, the methodology developed in this study for the assessment of visibility of lights can be easily extended to other types of lights.

As the boundary parameters to determine of the research program the requirements for the stop lights of category S2 were selected. The category S2 determines the lamps with variable luminous intensity and is used in vehicles equipped with the adaptive signal lights ASIS (called Adaptive Signaling Lamp System). Adaptability typically involves the use of two operating modes for a given light: day and night, being said that the adjustable value is the luminous intensity, while maintaining a constant lighting surface. The concept of the lights of category S2 is so similar, though much simplified, as compared to a lamp that is the subject of research. An additional advantage of using the existing requirements, in the case of implementing the production of the lamp with a variable lighting surface and luminance, is no need for profound changes in the Rules 7.

The values of luminous intensity required for the category S2 stop lights are in the range from 50 to 521 cd. It was selected the minimum, maximum, and one intermediate value. The lighting surface was limited to four values. Table 1 presents the values of luminous intensity and lighting surface chosen for the experiment, and the corresponding luminance values of the lamp lens.

Gray color in the table was used to designate the combinations of luminous intensity and lens luminance that can not be realized physically, on the developed model of the lamp. The reason is too small output light stream obtained from a single diode. Because, as demonstrated by tests, the actual luminance values found in the specific designs solutions of lamps are lower than 38 kcd/m^2, it was decided not to change the design of the lamp.

Number of factors affecting the perception of light signs is very large: the weather conditions, time of day, year season, degree of contamination of the lamp lens, or even a driver's individual characteristics. In order to reduce the number of cases considered, the study of a light signal perception was narrowed for typical ambient conditions. Moreover, given the need to conduct field tests (at open space) in strictly determined time-weather conditions which were out of control of the performer, the scope of tests was adapted to the existing conditions.

Table 1 Value of the luminous intensity and the lighting surface selected for the tests

Luminous intensity [cd]	Lens luminance [cd/m^2]			
	Lens surface area 9cm^2	Lens surface area 54cm^2	Lens surface area 108cm^2	Lens surface area 180cm^2
60	66 667 (case 1)	11 111 (case 2)	5 556 (case 3)	3 333 (case 4)
400	444 444	74 074 (case 5)	37 037 (case 6)	22 222 (case 7)
520	577 778	96 296	48 148 (case 8)	28 889 (case 9)

The results of light visibility tests

For the assessment of the visibility of the lamp light the questionnaire was designed, in which the participants of the experiment describe a sensed visual impressions. The evaluation of visibility was based on the five-point scale, where 1 means no visibility of a signal, 5 very strong discomfort, glare phenomena occurrence, 3 is the optimal value of the luminance and the lighting surface, when the light is clearly visible, but does not cause discomfort.

The assessment was conducted in daylight conditions, at a distance of both 150 meters and 5 meters and at night conditions, at a distance of observation of 5m. A distance of 150m simulates the conditions of observation during the drive on highway routes (motorways, express roads), where the observation distance is large. Observation range of 5m is to simulate the observation of light by a driver standing directly behind the observed vehicle. The situation occurs frequently when driving in traffic jam or waiting for a drive before the intersection. Long-term observation of the stop lights of high luminous intensity is tiring for the drivers, and it can also result in the occurrence of an interfering glare phenomena, and in consequence decrease the ability of the observer to perceive changes in traffic situations.

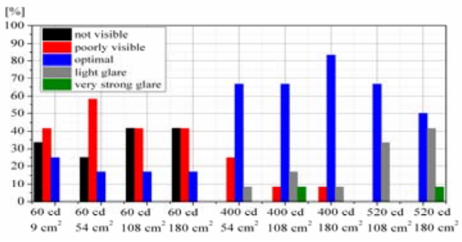

Fig. 11 Evaluation of the visibility of the lights in the day light conditions at the observation distance of 150m

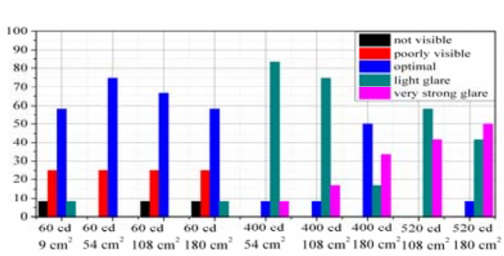

Fig. 12 Evaluation of the visibility of the lights in the day light conditions at the observation distance of 5m

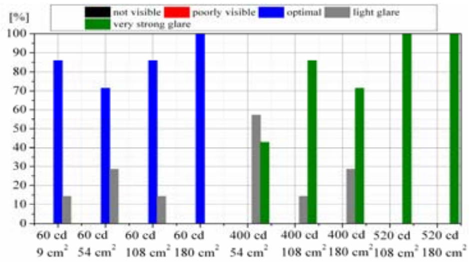

Fig. 13 Evaluation of the visibility of the lights in the night conditions at the observation distance 5m

The test results are shown in Figs. 11-13. The graphs present the visibility assessment of stop lights in accordance with the adopted scale of assessments for the individual combinations of luminous intensity and lighting surface. The value of the lighting surface was varied by changing the number of switched on LEDs. The results were scaled in the units [%], being said that 100% constitutes the total of all assessments for the given parameters of light. Each combination was assessed independently.

When assessing the visibility in daylight at a distance of observation equal to 150m (Fig. 11) for the lowest level of luminous intensity the most of respondents said that the light is not visible or poorly visible. Only 25% of the respondents for the case 1 and 15% for the cases 2, 3 and 4 determined the light as optimal. The increase in luminous intensity up to 400 cd greatly improves the perception of a light signal, with 65% of the respondents for the cases 5 and 6, and 85% of the respondents for the case 7 who rated the level of light visibility as optimal. If the level of luminous intensity amounts to 400 cd you can observe the influence of the lighting surface onto the rating of the light visibility. With the increase of the lighting surface the visibility of light improves too. With the area of 54cm^2, 25% of the respondents stated that the light is barely visible, while for the area of the lighting surface equal to 180cm^2, only 8% of them. At the same time, the rating of the visibility of light as optimal one increased from 65% to 85% of cases, with an increase of the lighting surface from 54 to 180cm^2. For the maximum luminous intensity allowed by the current legal environment, ie 520 cd, in the case of the lighting surface of 108 cm^2, 65% of respondents rated the light as the optimal one, which is a result similar to that for the luminous intensity of 400 cd. However, with the increase of the lighting surface the number of optimal ratings drops to 50%, while the number of respondents observing a slight glare increases. For the case 9, 10% of respondents stated very strong glare.

When assessing the visibility of the stop lights in the day light conditions at the observation distance of 5 m (Fig. 12) it was stated that the greatest number of optimal ratings was obtained for the lamp with the luminous intensity of 60 cd. Classification of light as the "optimal" was conditional on the lighting surface only to an insignificant extent. The most of optimal parameters, ie 75% was obtained for the lighting surface of 54 cm^2, for all other cases the number of optimal ratings was slightly smaller, namely 60% for the case 1 and 4, and 65% for the case 3.

Regardless of the lighting surface the share of “barely visible” ratings was relatively high, as compared to the test at an observation distance of 150m, and was equal to 25%. For the average level of luminance intensity (400 cd) it was observed an increase of a very strong glare with the increase of the lighting surface, from 10% for the surface area of 54 cm^2 up to 35% for the surface area of 180 cm^2.

For the greatest lighting surface of 180cm^2, there was a significant decrease in the observations designated as "light glare" (from 75% to 15%), with simultaneous increase of the optimal ratings (from 10% to 50%). For the highest level of luminous intensity, ie 520 cd the share of the "very strong glare" ratings increases up to 50%. compared to the luminance intensity of 400 cd. The lighting surface rise causes an increase in glare, thus reducing the proportion of light glare in favor of a very strong glare.

In the case of the visibility assessment of the stop lights at an observation distance of 5m at night hours (Fig. 13) it was stated that the most optimal ratings were given to the light with the luminous intensity of 60 cd. For this luminous intensity, no cases of poor visibility were stated. The change of the lighting surface cause a small change in the results of observations rated as a slight glare. For the cases 1, 2 and 3 the number of respondents evaluating light as the optimal amounts to 85%, 70% and 85% with a corresponding percentage of light glare. It is worth noting that, for the lighting surface of 180cm^2, the perfect combination of luminous intensity to the surface, at which 100% of respondents rated the visibility of the light as optimal, was achieved. For the intermediate luminous intensity of 400 cd, there was no optimal ratings. The visibility ratings are distributed between light glare and very strong glare , but it is difficult to confirm the dependence of ratings on the size of the lighting surface. This is due to the reaction of respondents to very high levels of light that make an objective assessment of the perceived stimuli difficult. The lamp of the highest luminous intensity amounting to 520 cd has been found by all respondents as causing a very strong glare, regardless of the lighting surface.

Conclusions

Based on the performed tests it was found that that the selection of basic light parameters of the lamp such as luminance of the lens and size of the lighting surface significantly affects the stop light perception comfort. Selection of optimal values is therefore essential to reduce the number of dangerous situations in traffic. It should be emphasized that the requirements (standards) for signal lights determine only the values of the luminous intensity, omitting the key parameters - as it turned out in result of the project implementation - such as luminance of the lens and the size of the lighting surface. It is therefore necessary to change the existing requirements and their much more rigorous definition.

The comfort of stop light perception depends strictly on the conditions of observation. Under the project the three selected driving situations were simulated: daytime at highway speed, daytime for vehicles standing one behind the other, and night time for vehicles standing directly one behind the other. For the first case the optimal luminous intensity was 400 cd at the lighting surface of 180cm^2 that give an average luminance of the lens equal to 22 kcd/m^2. For the second case, 60 cd and 54 cm^2 respectively, gave the luminance of the lens equal to 11 kcd/m^2 lens. While, for the third case: 60 cd and 180 cm^2 respectively, gave a luminance of the lens equal to 3.3 kcd/m^2. It is therefore justified to implement the adaptive signal lights that will have not only the luminous intensity adjustment possibility as so far, but what is new, the adjustment of the lighting surface, depending on external conditions.

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