DETERMINATION OF MAXIMUM VISIBILITY OF RAILWAY TRAFFIC LIGHTS

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ABSTRACT

The author examines the features of the light signaling system operating on the Bulgarian railways, designed to regulate movement of trains and ensure safety of people, goods and vehicles at railway crossings. On the basis of the heuristic approach, the maximum (limiting) range of visibility of signal lights of traffic lights is determined, a comparative analysis of data obtained in different weather conditions (including snow drifts), different time of day (day, night), at a different threshold of light sensitivity of the human eye depending on the strength of the light source (in particular, the specificity of mast and dwarf traffic lights) is suggested.

Keywords: *railway, light signaling, safety, traffic lights, visibility, range limits, heuristics, comparative analysis.*

Background. *According to the normative base operating on the railways of Bulgaria [1], at speed of trains up to 160 km/h, the signal indications of entrance, exit, passage, barrier and crossing traffic lights should have a range of visibility of at least 200 m, and of precautionary lights and before crossing – not less than 150 m.*

On lines with a speed of 160 to 250 km/h, the signal readings of the entrance, exit, passage and warning traffic lights imply a range of visibility of at least 400 m[1]*, while for barrier and traffic lights before crossings, visibility is not regulated, which means that in such areas intersections of railways and highways on the same level (crossings) are not anticipated.*

Shunting traffic lights must have a range of visibility of at least 200 m.

In connection with the introduction in Bulgaria of the so-called «high-speed signaling» of the second intermediate speed (100 km/h), a rectangular green strip was added to the well-known circular traffic lights.

In order to provide the range of visibility of traffic lights for lights of different colors, the minimum intensity of the traffic light heads on the optical axis is specified in [2] (Table 1).

The topic issue of the research refers to the maximum (limiting) range of visibility of the signal lights of railway traffic lights, including the green strip, using known [3] and not very well known premises, as well as some author's ideas.

Objective. *The objective of the author is to consider issues related to determination of maximum visibility of railway traffic lights.*

Methods. *The author uses general scientific and engineering methods, comparative analysis, evaluation approach, mathematical apparatus.*

Results.

1. Range of visibility of circular traffil light heads

1.1. Theoretical premises

It is known that if the observation of the object emitting light is visually performed, then the light of this object is reflected in the pupil of the observer's eye. As the distance to it increases, the reflection level decreases. At a certain distance, it will reach a value at which the eye will cease to sense light. This minimum illumination is called the «threshold of light sensitivity» of the eye to a point source of light (threshold illumination of the eye's pupil). The distance to the luminous object at the moment of disappearance of sensation of visibility is called the «maximum (limiting) range of visibility» of the object.

To perceive a luminous point (light from an object) with the eye, it is necessary that the illumination created by it in the pupil of the eye exceeds the threshold of the light sensitivity corresponding to a certain color. The values of this sensitivity day and night with an almost absolute transparency of the atmosphere and good visibility are given in Table 2 [3].

As can be seen from Table 2, the sensitivity of the eye decreases significantly during the day, which is due to the light background of the atmosphere, due to sunlight.

In order for the observer (in this case the driver) to be able to reliably perceive the signal at a certain distance during the day, in accordance with Kepler's law it is necessary to provide the light intensity along the optical axis from the object no lower than:

$$I = E_{pr.} \cdot L^2, \qquad (1)$$

where E_{pr} is a threshold of light sensitivity, lx; L – distance to the luminous object (range of visibility), m; I – light intensity along the optical axis to the object, cd.

In this case, the distance to the luminous object of a point source of light, such as a traffic light head, depends only on the strength of light, but not on its brightness.

Due to the partial absorption by the atmosphere of the light emitted by the object, it is necessary to use traffic lights with significant light intensity along the optical axis. Therefore, the minimum required force in real conditions, taking into account the state of the atmosphere, is based on the following empirical formula (Allard's law):

$$I = E_{pr.} \cdot L^2 \cdot \alpha^{-L} \cdot 10^6, \qquad (2)$$

where α is a coefficient of transparency of the atmosphere layer at a distance of 1 km; L – distance to the luminous object (range of visibility), km.

For the transparency coefficient α of the atmosphere, depending on its state, the values shown in Table 3 are known [3].

1.2. Range limits

Determination of the distance to the luminous object (range of visibility) L with the use of (2) for given I, $E_{pr.}$ and α becomes a difficult problem, since the unknown quantity L is also a power

[1] In the author's opinion, this requirement is controversial, because at these speeds the movement of trains must take place according to «electric visibility», which means automatic transmission to the driver's cab from the appropriately safe distance of information about the indications of railway traffic lights. Since the requirement is normative, then it is nonetheless accepted as a given.

Table 1

Color of light emitted	Light intensity on optical axis, cd	
	For mast traffic lights	For dwarf traffic lights
Red	1100	750
Yellow	2100	1600
Green	1500	1000
Blue	100	70
Lunar white (hereinafter white)	2000	1400

Table 2

Color of light	Threshold of light sensitivity $E_{pr.}$, lx		Color of light	Threshold of light sensitivity $E_{pr.}$, lx	
	Day	Day		Day	Day
Red	$0,6 \cdot 10^{-3}$	$0,8 \cdot 10^{-6}$	Yellow	$1,2 \cdot 10^{-3}$	$2,0 \cdot 10^{-6}$
Green	$0,9 \cdot 10^{-3}$	$1,2 \cdot 10^{-6}$	White	$2,0 \cdot 10^{-3}$	$3,0 \cdot 10^{-6}$
Blue	$0,8 \cdot 10^{-3}$	$1,0 \cdot 10^{-6}$	–	–	–

Table 3

Visibility class	Transparency coefficient of the atmosphere, α	Maximum visibility range (meteorological), km	Atmosphere condition
1	–	0,2	Strong fog
2	0,0004	0,5	Average fog
3	0,02	1	Weak fog
4	0,14	2	Very strong haze
5	0,38	4	Strong haze
6	0,67	10	Light haze
7	0,82	20	Satisfactory visibility
8	0,92	50	Good visibility

exponent. In this connection, it is proposed to solve the inverse problem, namely, for given L, $E_{pr.}$ and α to find the necessary light intensity for these conditions along the optical axis of the object and after several iterations to compare the results obtained for I with given minimum values for a specific type of traffic light heads. The range of visibility for the nearest received value of I in relation to the regulated light force is the desired range of visibility.

With a demonstration purpose in 1.2.1 and 1.2.2, the procedure for determining the range of visibility of traffic light heads for the state of the atmosphere «good visibility», α = 0,92 (visibility class 8 from Table 3) was performed.

The final results of applying the same procedure for the state of the atmosphere «strong haze», α = 0,38 (visibility class 5); «average fog», α = 0.0004 (visibility class 2) – are given in Table 7.

1.2.1. Determination of the range of visibility for the state of the atmosphere «good visibility in the afternoon» and the transparency coefficient α = 0,92.

For this state, the following results are obtained for I (Table 4). In colored cells, values that are greater than the minimum luminous intensity specified in [2] are indicated. The maximum visibility range L for this force is the value corresponding to I in the cell located to the left of the colored, or the average of two adjacent cells (colored and uncolored to the left of it).

From the results indicated in Table 4 and the graphs plotted on their basis (Pic. 1), it becomes clear that under given conditions the maximum (limiting) visibility range of the individual lights of the mast traffic lights will be:

- *red light ≤ 1300 m;*
- *green light ~ 1200 m;*
- *blue light ~ 350 m;*
- *yellow light ~ 1200 m;*
- *whire light < 1000 m.*

However, one should keep in mind the following assumptions:

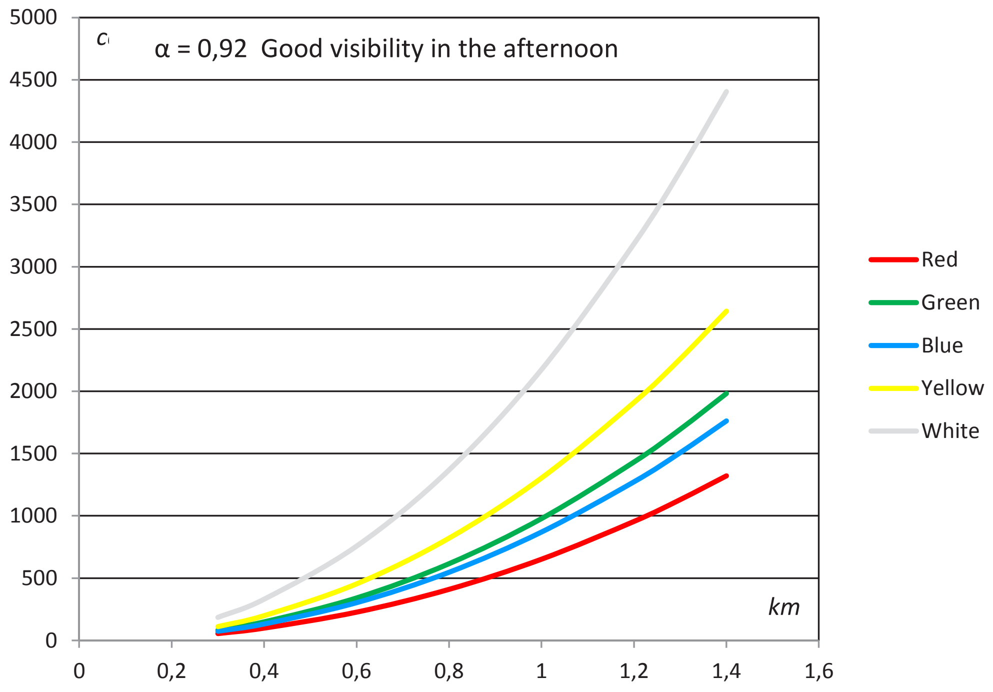
- *mast traffic lights, on which the heads of the corresponding lights are located, are located on the straight section of the track longer than the maximum (limiting) visibility range;*
- *it is assumed that the observer (driver) concentrates his attention on the optical axis of the object (the head of a traffic light) emitting light;*
- *fluctuations in the threshold of light sensitivity of the eye, which depend on age, health and emotional state of the observer, are not taken into account;*
- *the scatter of the supply voltage of the traffic lights, on which the fluctuations of I depend (in [2] such spreads are not specified) is not taken into account.*

From these assumptions it should be clear that in reality the obtained visibility range values may be lower, and therefore the results of calculations should be considered as the maximum possible (limiting) values.

For a case when the observer (driver) concentrates his attention not on the optical axis of the head of a traffic light emitting light, but at an angle ϕ with respect to it, formulas (1) and (2) take the form (Lambert's law):

Table 4

Color of light	Threshold of light sensitivity $E_{pr.}$, lx	L_i, km							
		0,3	0,4	0,6	0,8	1,0	1,2	1,3	1,4
	Day	I, cd	I, cd	I, cd	I, cd	I, cd	I, cd	I, cd	I, cd
Red	$0,6 \cdot 10^{-3}$	55	99	227	410	652	955	1130	1321
Green	$0,9 \cdot 10^{-3}$	83	149	341	616	978	1432	1695	1982
Blue	$0,8 \cdot 10^{-3}$	74	132	303	547	870	1273	1507	1762
Yellow	$1,2 \cdot 10^{-3}$	111	199	454	821	1304	1910	2260	2643
White	$2,0 \cdot 10^{-3}$	185	331	757	1368	2174	3183	3767	4405



Pic. 1.

$$I = E_{pr.} \cdot L^2 / \cos\phi, \quad (1')$$

$$I = E_{pr.} \cdot L^2 \cdot \alpha^{-L} \cdot 10^6 / \cos\phi. \quad (2')$$

*Using the previously stated procedure and based on the values of **I** regulated in [2] for dwarf traffic lights, Lambert's law should be applied when determining the range of visibility of the corresponding lights of these traffic lights. The use of (1') and (2') is also mandatory in cases of mast traffic lights, when the driver observes them not along the optical axis of the head, but at an angle ϕ with respect to it.*

1.2.2. Determination of the visibility range for the state of the atmosphere «good visibility at night» and the transparency coefficient $\alpha = 0,92$ (Table 5).

Analyzing the data of Table 5, it is necessary to note the obtained extremely low values of intensity along the optical axis I, which provide visibility at a distance of more than 1500 m. This is explained by the significantly higher sensitivity of the pupil of the eye at night (almost 1000 times).

In this regard, one more thing is asked for the assumptions already made:

• it is assumed that the dark background of the environment is not disturbed at night by other light sources, including moonlight (especially during a full moon).

2. Range of visibility of a rectangular green strip

The requirements for a rectangular strip of green color as to the dimensions of the construction (Pic. 2) are given in [2], but there are no requirements for the strength of the light emitted by it. However, since the green strip is a component element of the mast traffic lights, its maximum visibility range should obviously correspond to the visibility range of the remaining signal indications of these traffic lights.

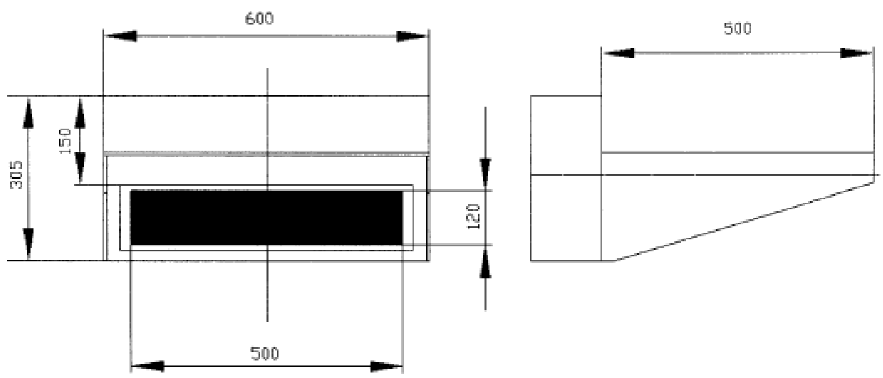
2.1. Theoretical premises

To determine the maximum (limiting) range of visibility of a rectangular green strip, the author suggests using the characteristic of the visual analyzer (eye) of the observer, called «separating ability».

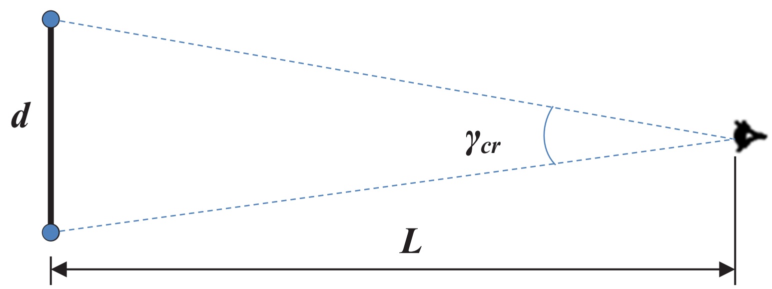
The separating ability of the human eye is evaluated by the critical angle of view (γ_{cr}). This is the minimum angle at which the eye can more often distinguish two separate boundary points of the image (Pic. 3). As this angle decreases, both points merge and are perceived as one. At normal vision, γ_{cr} is equal to one angular minute.

Table 5

Color of light	Threshold of light sensitivity $E_{pr.}$, lx	L_i, km							
		0,3	0,4	0,6	0,8	1,0	1,2	1,4	1,5
	At night	I, cd	I, cd	I, cd	I, cd	I, cd	I, cd	I, cd	I, cd
Red	$0{,}8 \cdot 10^{-6}$	0,074	0,132	0,303	0,547	0,870	1,273	1,762	2,040
Green	$1{,}2 \cdot 10^{-6}$	0,111	0,199	0,454	0,821	1,304	1,910	2,643	3,060
Blue	$1{,}0 \cdot 10^{-6}$	0,092	0,165	0,378	0,684	1,087	3,183	2,203	2,550
Yellow	$2{,}0 \cdot 10^{-6}$	0,185	0,330	0,757	1,368	2,174	3,183	4,405	5,010
White	$3{,}0 \cdot 10^{-6}$	0,277	0,496	1,135	2,052	3,261	4,775	6,608	7,649



Pic. 2.



Pic. 3.

Table 6

Limiting range of visibility (m), non-luminous objects				
Circular traffic light head	Rectangular green strip. Option 1		Rectangular green strip. Option 2	
By diameter	Vertically	Horizontally	Vertically	Horizontally
687	412	1719	120	722

Proceeding from this statement, it is possible to determine the maximum (limiting) range of visibility of ***a non-luminous*** *object, under which its boundaries are on the verge of confluence.*

2.2. Determination of range of visibility

In connection with the problem under consideration, it is of practical interest to determine the visibility range of two designs of a rectangular green strip, namely:

Option 1 *– a separate design with a radiating field dimensions of 120 mm vertically and 500 mm horizontally (Pic. 2).*

Option 2 *– a luminous strip of 35 mm vertically and 210 mm horizontally separated in the design of a circular traffic light head.*

In addition, a circular traffic light head with a diameter of 200 mm is used, regulated in [2].

The results of calculations for the limiting range of visibility of two indicated radiators, as ***non-luminous*** *objects, from the point of view of the separating ability of the eye, are as follows (Table 6).*

From Pic. 3 and Table 6 it becomes clear that with a rectangular radiator the visibility along the vertical will be critical, since both horizontal

Table 7

Light of head/strip of traffic lights		Theoretically defined limit visibility range L, m for the state of the atmosphere:					
	Good visibility, $\alpha = 0,92$		Strong haze, $\alpha = 0,38$		Average fog, $\alpha = 0,0004$		
	Day	Night	Day	Night	Day	Night	
Red		< 1300	> 1500	< 900	> 1500	~ 350	~ 800
Green – circular head		~ 1200	> 1500	~ 850	> 1500	< 350	~ 800
Rectangular strip of green light, Option 1	I = 1500 cd	720	> 1500	510	> 1500	210	~ 800
	I = 2000 cd	840	> 1500	570	> 1500	217	~ 800
Rectangular strip of green light, Option 2	I = 1500 cd	210	> 1500	148	> 1500	61	~ 800
	I = 2000 cd	245	> 1500	166	> 1500	63	~ 800
Blue		~ 350	> 1500	300	> 1500	~ 200	~ 600
Yellow		~ 1200	> 1500	~ 850	> 1500	< 350	~ 800
White		< 1000	> 1500	< 700	> 1500	< 325	~ 750

boundary lines of the object will be aligned in one line earlier than both more distant vertical boundary lines. Therefore, in this case, the maximum range of visibility horizontally should not be taken into account.

Moreover, in addition to the assumptions of 1.2.1, one should keep in mind here that the values indicated in the table should be perceived as limiting not only from the point of view of the separating ability of the eye, but also from the fact that this ability refers to the normal sight of the observer for good visibility of the atmosphere during the day.

The obtained values can be considered as a «passive visibility range», since they refer to **non-luminous** *objects.*

To determine the maximum visibility range of non-circular luminous objects in the afternoon, the author suggests the following heuristic approach.

We compare the «passive visibility range» from Table 6 for a circular traffic light head (687 m) with the limiting range of visibility of the same head (Table 4), but for the green light emitted by it in case of **good visibility during the day** *(1200 m). It is easy to calculate that the range of visibility of this head, which glows during the day, at a given light intensity along the optical axis of 1500 cd, is about 1,75 times greater than the «passive visibility range». On this basis, if we use the obtained heuristic coefficient (1,75) with respect to the visibility range of two types of rectangular green strip, provided that they have the same light intensity, both to each other and to the circular traffic light head of green color (1500 cd), then taking into account the specified vertical limit, the range of visibility of rectangular strips will be obtained for good visibility durig theh day, as follows:*

– for Option 1 – about 720 m;

– for Option 2 – about 210 m.

If the light intensity is approximately 2000 cd, then using the same results of Table 4 (for 1982 cd), a coefficient of 2,038 and a visibility range of 840 m for the strip of option 1 and 245 m for the strip of option 2 are obtained.

These theoretically obtained values for the visibility range of two options of rectangular green strips differ by less than 5–6 % from the results of the lighting tests known to the author, which indicates a very good convergence of the proposed approach.

*When the state of the atmosphere is «***average fog during the day***» and the light intensity along the optical axis is 1500 cd, a heuristic coefficient of 0,509 is obtained, and at a light intensity of about 2000 cd – 0,526. The range of visibility of both variants of green options in this state of the atmosphere during the day and the indicated values of the luminous intensity is given in Table 7.*

Quite differently, the question of visibility range of rectangular green strips **at night** *should be considered. Since the strip is a luminous object, in this case the following features of the observer's sight should be taken into account.*

At night, both the shape and size of the light source can not be determined, since vision perceives only light from the object, not seeing it. «Passive visibility» in this case is absent. Because of this, the object, be it round, elliptical, square or rectangular, will be perceived by the observer as a shapeless radiant source. It is easy to understand why this is so.

The picture of the light source in the retina consists of a set of separate points, each of which arises as a result of the stimulation of photosensitive cells, called because of their shape as rods and cones.

The length of the rods is about 0,06 mm, and of the cones – 0,035 mm. But if the image of the object on the retina is very small, it takes only two or three cones. Because of this, a sensation of a bright point appears, regardless of the actual shape of the light source. Therefore, it is impossible to estimate the angular dimensions of a luminous point object at night. For this reason, with the same light intensity along the optical axis, both versions of the rectangular green strip will have approximately the same visibility range at night with the range of visibility of the circular traffic light head of a green color (see Table 7).

3. Generalization of the results

The theoretical results obtained for the maximum (limiting) range of visibility of circular traffic light heads, as well as for rectangular strips in two versions, each with a light intensity of 1500 or 2000 cd, taking into account the assumptions from 1.2.1 and 1.2.2, are summarized in Table 7 for the state atmosphere «good visibility», «strong haze» and «average fog».

The author believes that for the mode of traffic lights «night» light intensity along the optical axis for traffic lights heads/strips of at least three times lower than the light intensity for the «day» mode is sufficient. Calculations show (Table 7) that under «good visibility» and «strong haze» conditions of the atmosphere, this three times reduced light intensity at night does not affect the visibility range, which remains above 1500 m, and for the state of the atmosphere «average fog» the visibility range at night will be more than twice the visibility range during the day, which is normal, given the higher sensitivity of the visual analyzer of the observer at night.

From the results indicated in Table 7 it follows that:

– For train speeds of up to 160 km/h and the required standard range of visibility of 200 m for indications of entrance, exit, passage, barrier and crossing traffic lights, as well as 150 m for warning and traffic lights before crossings:

– all the lights of the traffic lights meet the regulatory requirements for visibility range day and night in conditions of good visibility of the atmosphere, strong haze and average fog;

– Option 1 of a rectangular green strip satisfies the regulatory requirements of visibility range day and night in conditions of good visibility of the atmosphere, strong haze and average fog. For average fog conditions in the daytime, the values obtained are close to normative;

– Option 2 of a rectangular green strip meets the regulatory requirements for visibility range at night in conditions of good visibility of the atmosphere, strong haze and average fog. For conditions of good visibility, in the daytime the obtained value of the visibility range of this strip is more acceptable at I = 2000 cd, because at I = 1500 cd, it is closer to the normative one. Option 2 of the rectangular green strip does not meet the regulatory requirements for visibility range in the daytime in conditions of strong haze and average fog for both values of I;

– For train speeds from 160 km/h to 250 km/h and the required standard visibility range of 400 m for readings of entrance, exit, passing and warning traffic lights:

– all readings of circular traffic lights heads meet the regulatory requirements for the range of visibility at night in conditions of good visibility of the atmosphere, strong haze and average fog, and for visibility range in the daytime – only in conditions of good visibility and strong haze. The round traffic light head of blue light satisfies the regulatory requirements of the visibility range in the daytime and in the conditions of average fog of the atmosphere;

– Option 1 of a rectangular green strip meets the regulatory requirements for visibility range at night in conditions of good visibility of the atmosphere, strong haze and average fog, and in the daytime – only in conditions of good visibility and strong haze;

– Option 2 of a rectangular green strip meets the regulatory requirements for visibility range at night in conditions of good visibility of the atmosphere, strong haze and average fog. Option 2 of the green strip does not meet the regulatory requirements for visibility range in the daytime in conditions of good visibility, strong haze and average fog.

From the analysis above, it follows that for conditions of average fog during the day, the regulated minimum light intensity of the traffic lights heads\strips is insufficient to provide a visibility range of 400 m.

Conclusions.

The procedure is proposed for theoretical determination of the maximum (limiting) range of visibility of traffic lights heads signaling by high-speed signaling (but not only), both for mast and dwarf traffic lights;

The heuristic approach is proposed to determine the maximum (limiting) range of visibility during the day of non-circular (rectangular / square / elliptical) luminous objects;

By the described procedure and the given light intensity emitted by the traffic light head/strip, it is possible to determine the maximum (limiting) range of visibility and to develop nomographs for different color of traffic lights at different atmospheric conditions;

The proposed procedure allows to solve the inverse problem, namely, for a given standard range of visibility and the boundary condition of the atmosphere, to determine the necessary intensity of light emitted by a traffic light head/strip;

The performed studies show that with regard to the visibility range of traffic lights heads/strips, the conditions for their perception during the day are determining, as well as the vertical dimensions of the rectangular radiators/strips;

The light intensity along the optical axis of traffic lights heads/strips for the «night» mode may be at least three times lower than the light intensity for the «day» mode;

For average fog conditions, in the daytime, the minimum light intensity specified in [2] along the optical axis of the traffic lights is insufficient to provide a visibility range of 400 m.

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