CONCEPTION / DESIGN OF LIGHTING SYSTEMS FOR URBAN TRAFFIC ROADS

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Abstract

The paper treats an up-to-date conception of lighting systems for medium and high speed traffic roads, based on international research, CIE norms and recommandations, corroborated with researches made by Lighting and Electrical Installations Chair within Bucharest Technical University of Constructions and by Romanian National Committee of CIE (CNRI). On this solid base, an approach structure is suggested. It starts with quantitative and qualitative aspects of urban luminous environment in connection with traffic specific requirements/criteria, tackling adequate solution/solutions step-by-step. It also realises necessary calculation structure regarding road luminance values, as well as drivers visual protection about physiological glare and psychological glare. So, an up-to-date treatment of road lighting systems designing is emphasized, that was also applied in Romania, during last years.

1 Introduction

This paper suggests the evidence of modern conception of lighting systems for medium or high speed traffic ways (streets and highways). CIE (Commission Internationale d'Éclairage) researches, experience and recommendations are used, corroborated with experience and researches of Lighting and Electrical Installations Chair of Bucharest Technical University of Constructions (UTCB), Faculty of Installations.

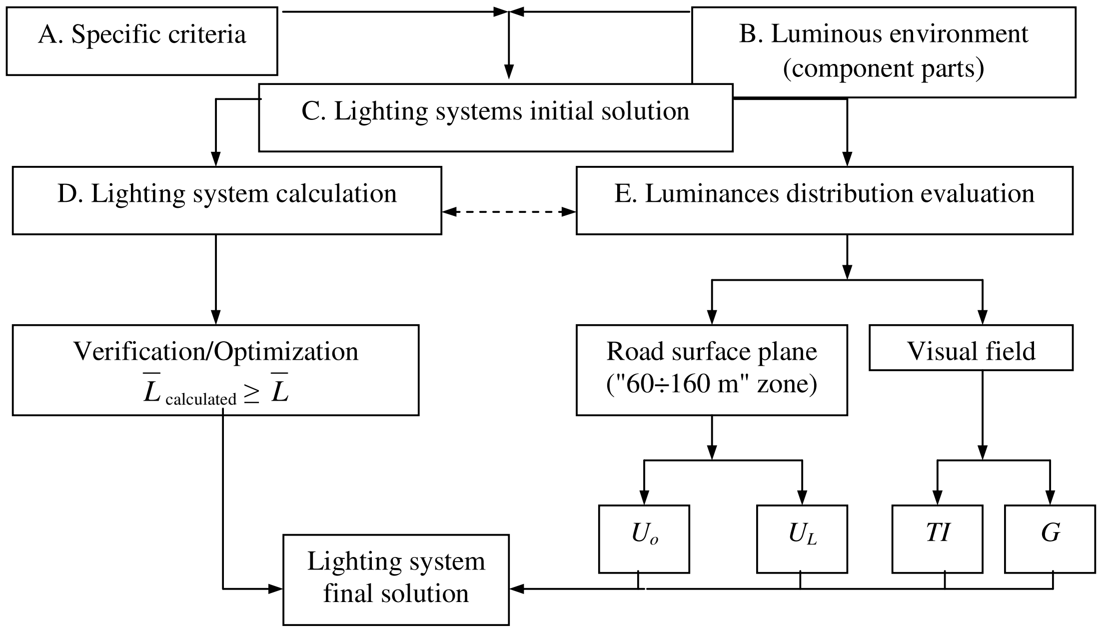
2 Conception of lighting systems for traffic ways

Like any other lighting systems, recommended original structure of lighting systems for traffic ways requires a logical composition including the following component parts (Figure 1):

A. specific requirements (criteria);
B. determination of quantitative and qualitative components of luminous environment that can satisfy the needs of visual comfort, traffic security, functionality and connected esthetical aspects;
C. selection of system solution on the basis of relevant reasons from stages A and B;
D. quantitative calculations of lighting system on the basis of reference dimension: average luminance ($\overline{L}$) on road surface;
E. qualitative evaluation of lighting system from luminance distribution and visual field points of view.

Using this algorithm step-by-step, correct final solution can be reached, which can realize decisive quantitative and qualitative requirements.

In Figure 2, these specific criteria of lighting systems for medium and high speed traffic ways are shown; these criteria must be taken into account in conception of lighting systems.



$\overline{L}$ - average luminance of road surface
U_o - overall uniformity of road luminance
U_L - longitudinal uniformity of road luminance
TI - threshold increment
G - glare control mark

Figure 1 Structure of lighting systems conception approach for traffic ways

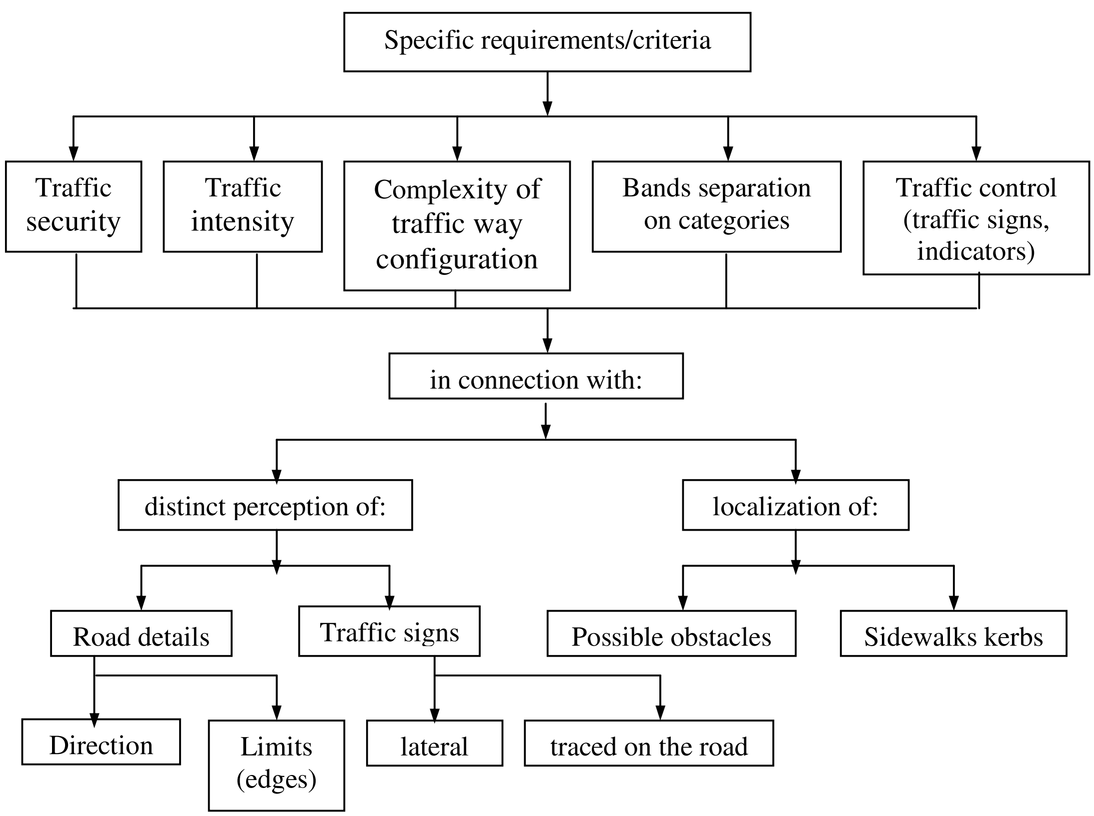


Figure 2 Specific criteria in road traffic

3 Decisive aspects of luminous environment within road lighting systems

Depending on these aspects, decisive quantitative and qualitative components of luminous environment must be chosen (Figure 3).

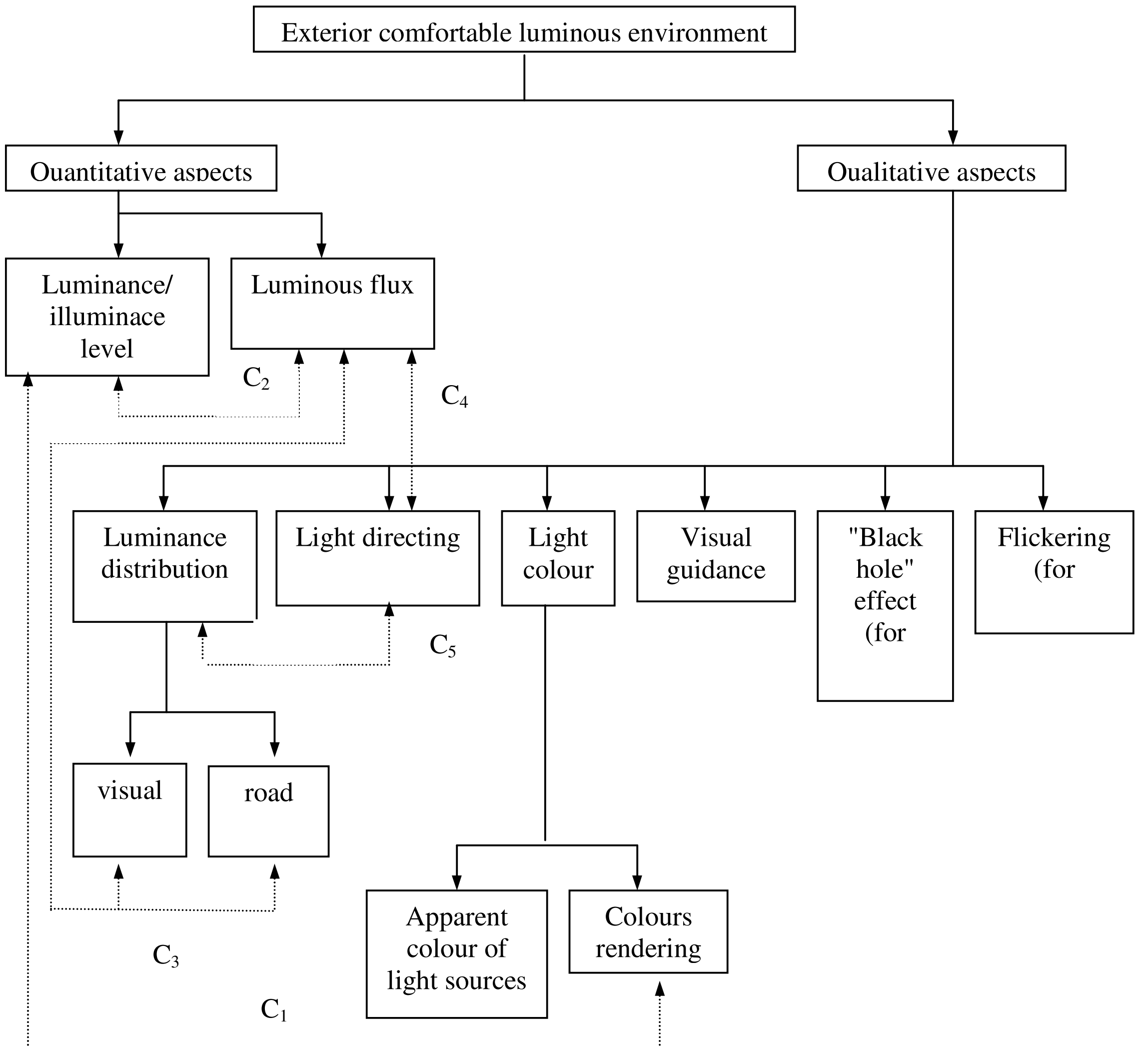


Figure 3 Structure of comfortable luminous environment for road traffic, including connection relations (C_1, C_2, C_3, C_4, C_5)

3.1 Quantitative aspects

3.1.1 Average value of luminance level, $\overline{L}$

According to latest CIE recommendations, [4], $\overline{L}$ represents the decisive quantitative aspects, its values being between 0.5 and 2 $cd.m^{-2}$, for different traffic ways categories (lighting classes: M_1, M_2, M_3, M_4, M_5). Traffic ways are classified depending on the following aspects:

- traffic density;
- complexity of road layout;
- traffic control;
- separation of different types of road users.

One must not forget that luminance, due to its active nature for human eye (direct connection with retina illumination) was introduced, as a reference, in 1960 at international level and in 1970 in Romania, thanks to researches of present Lighting Chair of UTCB.

3.1.2 Surround ratio, *SR*

According to [4], it is necessary to extend lighting system in traffic ways nearby zone, 5 m wide, in order to reduce contrast between road average illuminance and this zone average illuminance, that leads to reduction of this discomfort factor, with direct influence on driver visual capacity. This ratio is "surround ratio, *SR*":

$$SR = \frac{\overline{E}_{nz,'5m'}}{\overline{E}_{r.'5m'}} \tag{1}$$

where:

$\overline{E}_{nz,'5m'}$ - average illuminance on strips, 5 m wide or less if space does not permit, which are adjacent to edges of both road sides

$\overline{E}_{r,'5m'}$ - average illuminance on strips, 5 m wide or half the road width, whichever is smaller, on the road.

Minimum value is 0.5 for M_1, M_2 and M_3 lighting classes.

3.1.3 Luminous flux distribution

For medium and high speed traffic ways, luminous flux distribution is exclusively only direct.

3.2 Qualitative aspects

From qualitative point of view, the three decisive elements are: luminances distribution, light colour and visual guidance.

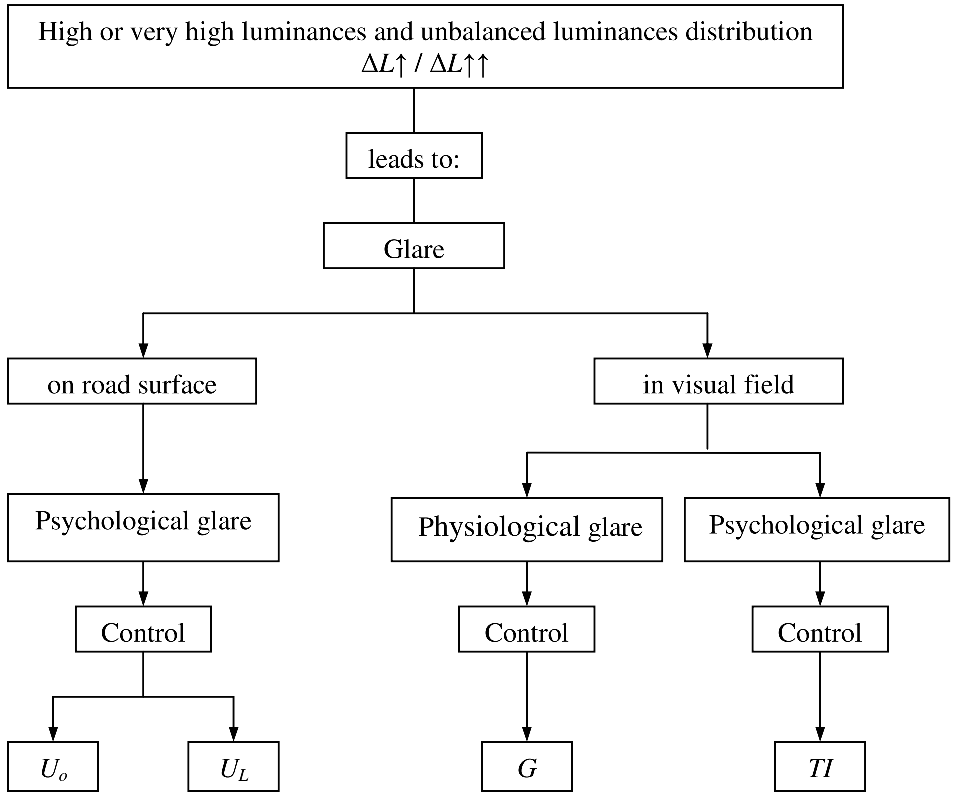
3.2.1 Luminances distribution

It is one of fundamental qualitative aspects for obtaining traffic comfort and security, by avoiding the two types of glare:

- physiological glare, directly produced in visual field by luminaires within "60÷160 m" zone;
- psychological glare, by:
  - luminous distribution non-uniformity on road surface;
  - light sources/luminaires number, which are seen on dark environmental background in visual field.

In figure 4, scheme of these effects is presented.

Discomfort glare produces a bigger or a smaller uncomfort depending on "provocative" source. This leads to visual and mental tiredness. It also can produce, depending on luminance value, a state varying from uncomfort to visual incapacity that can determine, in extremis, impossibility to distinguish some road elements/structures. Finally, it can lead to control loss besides visual/mental perturbation.



L - luminance of road surface
U_o - overall uniformity of road luminance
U_L - longitudinal uniformity of road luminance
TI - threshold increment
G - glare control mark

Figure 4 Effects of luminances non-uniform distribution

3.2.2 Directioning and modeling

They come true implicitly by correct luminous intensities distribution structure of luminaires (non-uniform) and eventually by luminaires adequate orientation compared to road surface.

3.2.3 Light apparent colour

It is a very important aspect in traffic and in urban luminous environment.

From sources point of view, in the past there were only two possibilities:

- low-pressure mercury lamps (fluorescent MLP) or high-pressure mercury lamps (white-blue colour MHP);
- low-pressure sodium lamps (monochromatic yellow colour SLP).

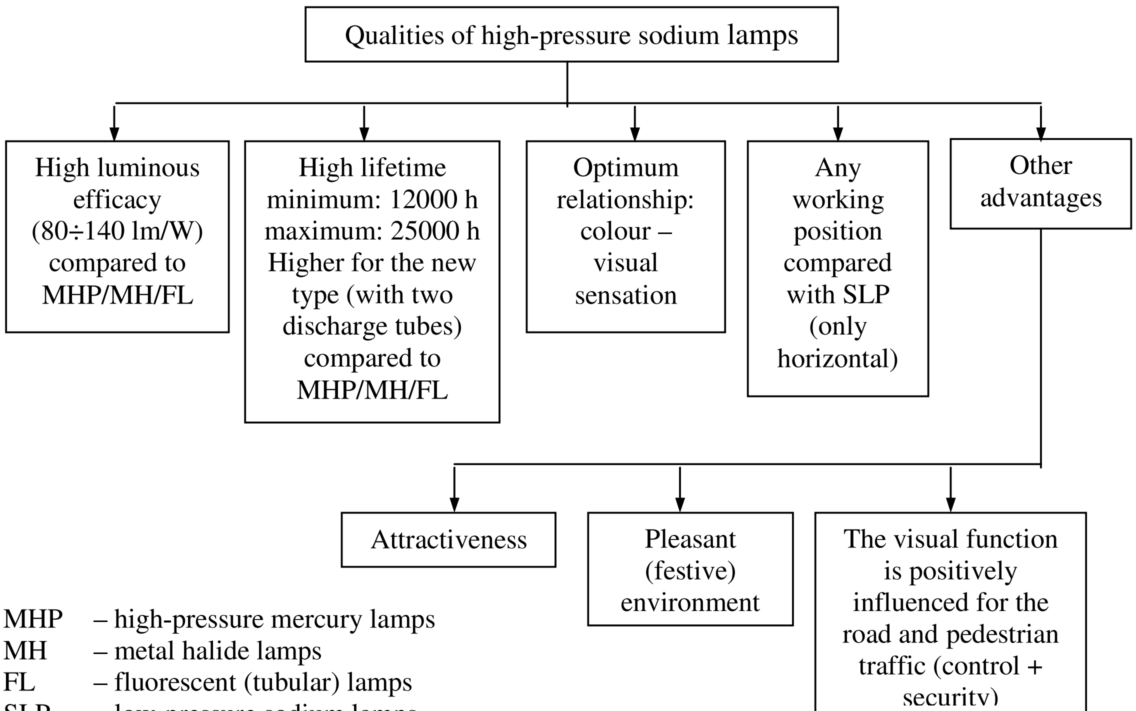
Starting from 1970, high-pressure sodium lamps (SHP) are used. This source has distinct qualities from both visual-esthetical and energy performance points of view:

- visual, thanks to spectral emission "evolute" curve that has maximum value approximately at the same wavelength as "relative visibility curve";
- yellow-gold colour of emission, that creates a exquisite pleasant, warm, attractive and esthetical environment;

- luminous efficacy is double compared to classical high-pressure mercury lamps and with 60÷80% higher than metal halide lamps and fluorescent lamps;
- lifetime (12000÷25000 h) is more than double compared to high-pressure mercury lamps and metal halide lamps.

High-pressure sodium lamp represents optimum solution from colour-visibility-aesthetics-energy consumption points of view, although colours rendering is low, aspect that is not generally irritating in evening/night conditions.

In Figure 5, qualities of high-pressure sodium lamp are presented. It must be mentioned that the new generation of high-pressure sodium lamp with xenon has a higher efficacy (with ≈20%) compared to standard variant.

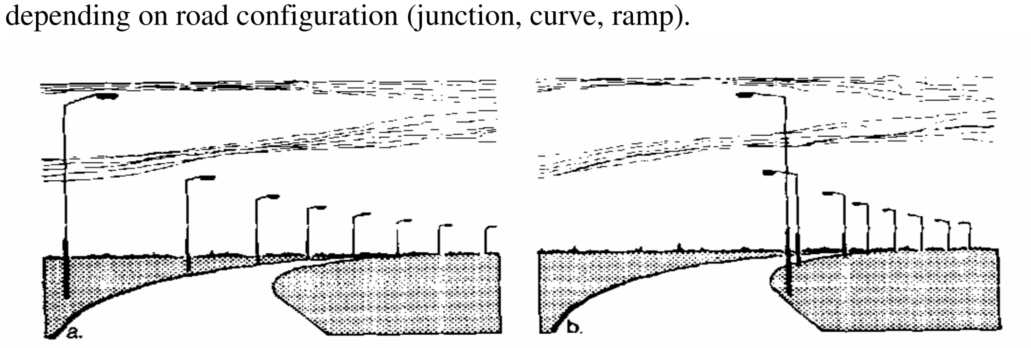


MHP – high-pressure mercury lamps
MH – metal halide lamps
FL – fluorescent (tubular) lamps
SLP – low-pressure sodium lamps

Figure 5 Qualities of high-pressure sodium lamp

3.2.4 Visual guidance

It is a very important qualitative aspect for traffic and can usually be realized by adequate solutions choice depending on road configuration (junction, curve, ramp).

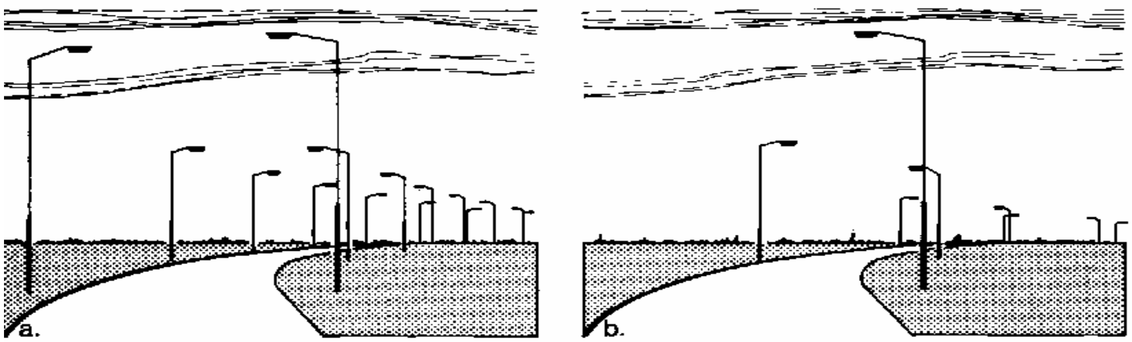


a – luminaires along outside of curve (good) b - luminaires along inside of curve (confusion)

Figure 6 Visual guidance in curves for single-sided arrangement

Generally speaking, single-sided arrangement with luminaires along outside of the curve represents an optimum solution for narrow streets (Figure 6).

For wide streets curves, opposite arrangement represents a good visual guidance, compared to staggered arrangement that can create visual confusion (Figure 7).



a – opposite arrangement (good) b – staggered arrangement (confusion)

Figure 7 Visual guidance in curves for bilateral arrangement

In visual guidance realized by colours changing, studied and elaborated in the sixties, distinct colours are used depending on road importance (e.g.: sodium lamps for radial streets and low/high pressure mercury lamps for secondary streets). Today, this kind of visual guidance appears to be old-fashioned taking into account the following reasons:

- visual adaptation neglect in research, from chromatic point of view, which represents a requirement of driver visual system. If it is repeated, it can lead to visual/mental tiredness and self-control diminution;
- research was made in the sixties only with low-pressure sodium lamps compared to mercury lamps and it is not fair to be spread to high-pressure sodium lamps, which are very different from the spectral point of view of apparent colour and colours rendering;
- permanent colours change degrades "unitary and harmonious ensemble" image of evening/night urban environment; permanent mixture of two colours (which is still seen in Romania, although there are some improvements in the last years) creates a visual "mixed up" environment, with unesthetical results (kitsch).

Using experiments, international researches proved an aspect harder to be understood at first interpretation: accident risk when passing from white-blue colour (mercury) with low luminance level to warm yellow colour with high luminance level (for main streets). These accidents were produced by impossibility of momentary chromatic adaptation, together with "apparent security" sensation (when passing from low to high luminance) and with an eventual stress/tiredness state of driver.

Taking into account these reasons and experiments made by Lighting Chair of UTCB, the only modern solution is the unitary, general one with high-pressure sodium lamps, good colours rendering not being necessary in traffic and urban environment.

By way of exception, when colours rendering effect in the whole environment of a zone is wanted, one may use, with great prudence in esthetical-architectural conception, the following light sources:

- metal halide, with smaller colour temperature, T_c in order to maintain it close to day colour;
- high-pressure sodium (white) lamps: R_a=80, T_c=2500 K or R_a=60, T_c=2200 K ("comfort") - harmonized solution with whole "high-pressure sodium" urban environment.

As for the other two qualitative aspects ("black hole" effect and flicker effect), they appear in road tunnels, which is not the subject of this paper.

4 Choice of road lighting system solution (location, components)

It is realized based on luminous environment quantitative and qualitative analyzed aspects, in connection with geometrical (road width, poles height) and luminotechnical elements (luminaire type from luminous flux distribution and visual protection points of view).

Road lighting systems calculation is realized based on luminance as reference. Calculation methods are presented in Figure 8.

Calculation methods depending on luminance

- Global method ("utilization factor")
- "Point calculation" method
- Graphs-analytical method ("computer-generated iso-cd.m^{-2} diagrams")

"Luminances map" for "60÷160 m" zone

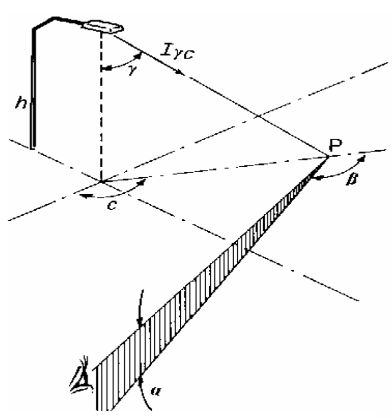
$$\overline{L}_{\text{calculated}} \geq \overline{L}$$

$$U_{o\ \text{calculated}} = \frac{L_{\min,'road'}}{\overline{L}} \geq U_o$$

$$U_{L\ \text{calculated}} = \frac{L_{\min,'lane'}}{L_{\max,'lane'}} \geq U_L$$

$\overline{L}$ - average luminance of road surface
U_o - overall uniformity of road luminance
U_L - longitudinal uniformity of road luminance

Figure 8 Road lighting systems calculation methods depending on luminance



$I_{\gamma,C}$ – luminous intensity of luminaire in point direction on road [cd]
α – observation angle (from horizontal) [degrees]
β – angle between light incidence plane and observation plane [degrees]
γ – angle of light incidence [degrees]

Figure 9 Luminous intensity and decisive angles

Of course, "point calculation" method is the most used today in modern lighting software and offers pertinent and sure analysis possibility of whole "controlled" zone.

Global method ("utilization factor") and graphs-analytical method ("computer-generated iso-cd.m^{-2} diagrams") represent a relative far-off epoch (when personal computer was not generalized) and offer only approximate punctual and medium values.

"Point calculation" method is based on connection between illumination at a point P, E_{PH} and corresponding luminance, L_{PH}:

$$L_{PH} = q \cdot E_{PH} \qquad [\mathrm{cd.m^{-2}}] \tag{2}$$

where:
q – luminance coefficient that depends on driver ("observer") position and light source relative to the point on road surface under consideration [cd.m^{-2}.lx^{-1}] (Figure 9)

Taking into account that:

$$E_{PH} = M_f \cdot \frac{I_{\gamma,C} \cdot \cos^3 \gamma}{h^2} \tag{3}$$

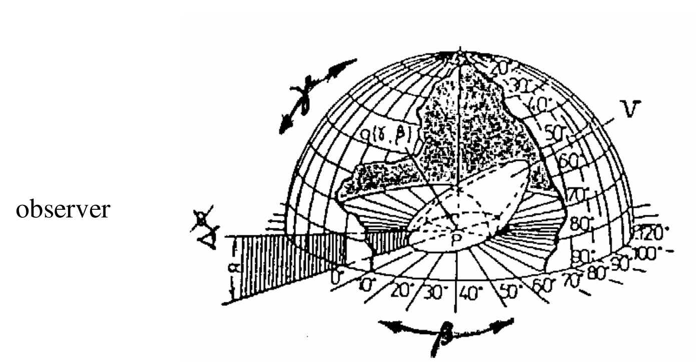
It results that:

$$L_{PH} = M_f \cdot q \cdot \frac{I_{\gamma,C} \cdot \cos^3 \gamma}{h^2} \tag{4}$$

or:

$$L_{PH} = M_f \cdot \frac{I_{\gamma,C} \cdot r(\beta,\gamma)}{h^2} \tag{5}$$

where:
M_f – maintenance factor (light loss factor)
$r(\beta,\gamma)$ – reduced luminance coefficient, specified in CIE norm, depending on "road class" from road surface point of view.



$q(\gamma, \beta)$ – luminance coefficient [cd.m^{-2}.lx^{-1}]
α – observation angle (from horizontal) [degrees]
β – angle between light incidence plane and observation plane [degrees]
γ – angle of light incidence [degrees]
V – volume of reflected intensities distribution

Figure 10 Spatial representation of luminance coefficient

Road surface classification is realized depending on "surface degree of lightness", defined by:

- average luminance coefficient, Q_o;
- surface degree of specularity, S_1.

$$Q_o = \frac{\int_0^{\Omega_o} q \cdot d\Omega}{\Omega_o} \tag{6}$$

where:

Ω_o – solid angle containing all those directions of light incidence at point P on road under consideration that are taken into account in average process (Figure 10)

$$S_1 = \frac{r(0,2)}{r(0,0)} \tag{7}$$

where:

$r(0,2)$ – reduced luminance coefficient for β=0 and γ=2
$r(0,0)$ – reduced luminance coefficient for β=0 and γ=0

Depending on S_1 and Q_o, road surfaces classification can be realized in:

- four classes, according to CIE old system (Table 1);
- two classes, according to CIE new system (Table 2).

Table 1 R-classification of road surfaces (old)

Class	S_1 limits	R system		Reflection type
		Standard S_1	Normalized Q_o	
R I	$S_1 < 0.42$	0.25	0.10	diffuse
R II	$0.42 \le S_1 < 0.85$	0.58	0.07	approximately diffuse
R III	$0.85 \le S_1 < 1.35$	1.11	0.07	slightly glossy
R IV	$1.35 \le S_1$	1.55	0.08	glossy

Table 2 C-classification of road surfaces (new)

Class	S_1 limits	Standard S_1	Normalized Q_o
C I	$S_1<0.4$	0.24	0.10
C II	$S_1 \ge 0.4$	0.97	0.07

Luminances distribution evaluation (which can lead, when equilibrium is not present, to physiological glare and psychological glare on road surface or in visual field) is realized according to the following methodology, being a "sine qua non" condition of system quality. In order to obtain visual comfort and traffic security, reference minimum values must be respected:

a. *Evaluation of psychological glare on road plane* is realized using (Figure 11):

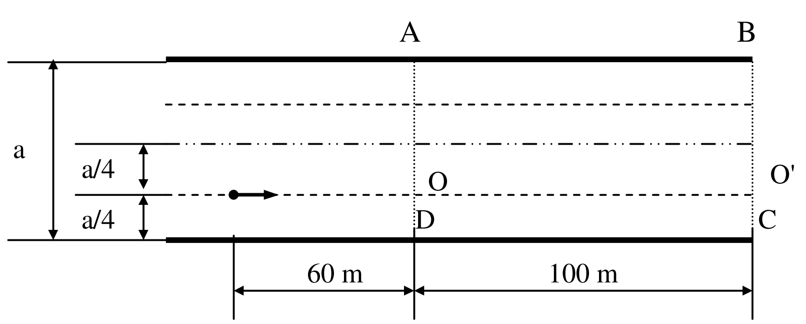


Figure 11 Determination of U_o and U_L factors

- overall uniformity of road luminance, U_o (ABCD surface);
- longitudinal uniformity of road luminance, U_L (OO' line on observer moving way, within "60÷160 m" zone).

Light from glare sources scattered in retina direction will cause a bright veil to be superimposed on sharp image of scene in front of observer. Veiling luminance, L_V can be calculated using Stiles-Holladay empirical formula:

$$L_V = k \cdot \sum_{i=1}^{n} \frac{E'_{eye'i}}{\theta_i^2} \qquad [\text{cd.m}^{-2}] \tag{11}$$

where:

$E'_{eye'i}$ – illuminance on eye (in a plane, V perpendicular to line of sight) caused by the i^{th} glare source, S_i [lx] (Figure 12)

θ_i – angle between viewing direction and direction of light incidence on eye of the i^{th} glare source, S_i [degrees]

k – age factor (for calculation purposes taken as 10)

Admitted maximum values of *TI* are:

- 10%, for M_1, M_2 and M_3 lighting classes;
- 15%, for M_4 and M_5 lighting classes.

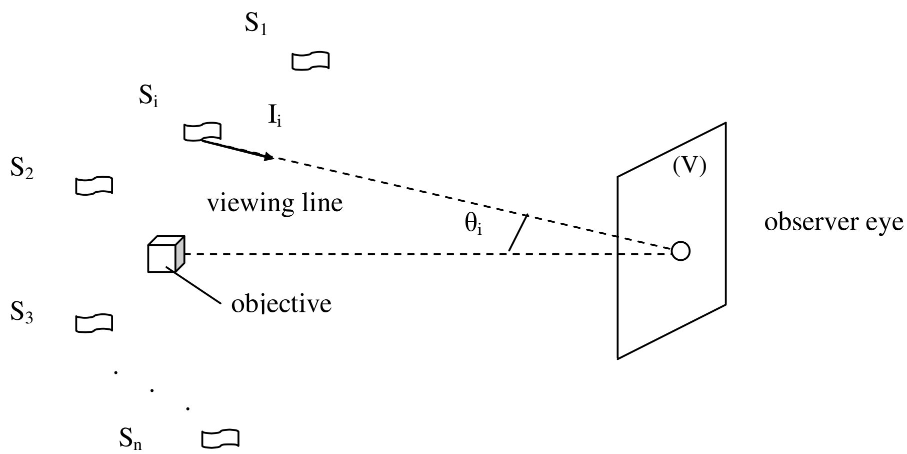


Figure 12 Determination of veiling luminance, L_V on observer retina

c. *Evaluation of physiological glare* is realized using glare control mark, *G*.
After tests realized using a large number of observers, international research elaborated an empirical formula for *G*:

$$G = 13.84 - 3.31 \cdot \log I_{80} + 1.3 \cdot (\log \frac{I_{80}}{I_{88}})^{0.5} - 0.08 \cdot \log \frac{I_{80}}{I_{88}} + 1.29 \cdot \log F + 0.97 \cdot \bar{L} + 4.41 \cdot \log h' - 1.46 \cdot \log p + c \tag{12}$$

where:

I_{80} – absolute luminous intensity at an angle of 80° to downward vertical, in a vertical plane parallel to road axis [cd]

$\frac{I_{80}}{I_{88}}$ – ratio of luminous intensities at an angle of 80° and at an angle of 88° to downward vertical, in a vertical plane parallel to road axis

F – orthogonal projected flashed area of luminaire in a direction of 76° to downward vertical, in a vertical plane parallel to road axis [m^2]

$\overline{L}$ – average luminance of road surface [cd.m^{-2}]
h' – vertical distance between eye level and luminaire [m]
$h' = h - 1.5$, where h is luminaire mounting height [m]
p – number of luminaries per kilometer [no.km^{-1}]
c – colour correction factor:
c=0.4 for low-pressure sodium lamps
c=0 for other lamps

Formula for G is valid for following ranges of values:

$50 < I_{80} < 7000$

$1 < \frac{I_{80}}{I_{88}} < 50$

$0.007 < F < 0.4$

$0.3 < \overline{L} < 7$

$5 < h' < 20$

$20 < p < 100$

number of luminaires rows = 1 or 2

In Table 3, there are presented values of a scale used to assess physiological glare, according to CIE.

Table 3 Scale used for assessing physiological glare

Index	Glare	Assessment
1	unbearable	bad
3	disturbing	inadequate
5	just admissible	fair
7	satisfactory	good
9	unnoticeable	excellent

5 Conclusions

This paper offers a modern conception structure of lighting systems for medium and high speed traffic roads (streets, highways, tunnels, passages) on the basis of decisive aspects:

- specific criteria of connection with luminous environment;
- calculation depending on luminance;
- evaluation of luminances distribution.

This is a complex modality that leads to accomplishment of a lighting system capable to provide for traffic luminous comfort and security.

Bibliografie

1. Bianchi C., *Luminotehnica*, vol. I, II, Ed. Tehnică, Bucureşti, România, 1990
2. Bianchi C., ş.a., *Culoarea aparentă a luminii în sistemele de iluminat urban,* Light & Lighting 2000 Proceedings, Bucureşti, România , 2000
3. Bommel, Van W.J.M., De Boer J.B., *Road Lighting,* PHILIPS Library, Eindhoven, Holland, 1980
4. CIE, *Recommendation for the Lighting of Roads for Motor and Pedestrian Traffic,* Publication no. 115, Vienna, Austria, 1995
5. PHILIPS, *Lighting Manual*, 5th Edition, Eindhoven, Holland, 1993
6. *Manualul inginerului de instalaţii,* Partea I-a: *Iluminat*, în curs de apariţie
7. ASRO, *ILUMINATUL CĂILOR DE CIRCULAŢIE. Condiţii de iluminat pentru căi de circulaţie destinate traficului rutier, pietonal şi/sau cicliştilor şi tunelurilor /pasajelor subterane rutiere,* SD 13433:1999, Bucureşti, România, 1999

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