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Mathematical model of type approval requirements for headlighting

Tomasz Targosinski
Motor Transport Institute
Warsaw, Poland
tomasz.targosinski@its.waw.pl

Abstract—Type approval requirements for headlighting are divided to photometrical requirements in component regulations and to installation requirements describing position on vehicle, initial aiming and leveling tolerances. In addition light sources are standardized and type approved. Design of this system of requirements is based on mathematical model of road illumination. This model was not explicitly expressed even is internally included in requirements. But the way of defining of requirements somehow reflect this model. At a time when requirements were created for the first time technology of light sources and headlamps was very special and different than today – low voltage double filament and paraboloidal reflector with rifles glass lens. Simplifications and imperfections of mathematical model used in creating regulation more than 50 years ago significantly influenced for headlamp design evolution and finally for road illumination and glare.

In the paper is presented reconstruction and analysis of the mathematical model and its influence for headlights performance, measurements and verification. This model is imperfect and allow for significant differences in quality of road illumination. It is also analyzed how it works in connection with contemporary headlamps design and technology and practice.

Keywords-component; type approval, headlighting

I. INTRODUCTION

Driving during night time require road illumination by luminaries. Human perception is adated to natural daytime illumination. There is bright background and objects important for safety are rather dark. Also indoor illumination has similar features. Street lighting situation is somehow similar to daylight because light is radiated from the top and it is illuminated road and its surrounding at relatively high distances from driver position. From road traffic safety point of view visibility distance is usually much longer than stopping distance. Essential difference between daylight and street lighting concern luminance levels observed by the driver.

Different situation occur when illumination is provided by vehicle headlamp. It is difficult to imagine another way of light emitting e.g. from the top and wide illuminated surroundings. Illumination done by headlamps change visual conditions significantly. Background is black or significantly darker then objects which are illuminated by headlamps. In such situation perception has "negative" character. The visibility in daylight is naturally impaired by distance because of change of angular size of objects with distance. During nighttime by headlamp illumination visibility is additionally affected by significant change of illuminance with distance, approximately with inverted square of distance. Headlamps positioned in front side of vehicle emit concentrated light generally in direction parallel to vehicle axis. The angles of illumination are small and simplified assumption that cosine is equal to one works very well. Outside this natural physical and physiological phenomenon are performance of headlights. For contemporary headlighting there are three important factors: light source, headlamp optical design and headlamps location on the vehicle including aiming an leveling. Similarly there are tree aspects of UN ECE type approval system. There are separately regulated but creates whole system. This way of defining requirements for headlamp as a rule was defined nearly 60 years ago. A least the third generation of people is learned on the base such defined requirements. They are mostly specialist from industry, test houses and type approval authorities. Many of them, especially younger, not even begin to imagine that this system is based on given assumptions and simplifications. Present type approval system is sometimes treated axiomatically as the only possibility. It is because everybody "know" how headlights looks like and how work.

II. REQUIREMENTS FOR VISIBILITY

From the point of view of road traffic engineering, the visibility of the road is the property that allows users to have visual access to the appropriate distance in of the road, especially in the area allowing to identify the traffic situation at the time, and to adapt driving. It is the primary factor, exerting a significant influence for driving safety. It is estimated through the necessary distance (visibility distance) between moving vehicle and obstacle. From this distance obstacle must be noticed and driver could safely perform the appropriate maneuver. In typical daytime driving can be distinguished [1]:

- concentrated control around 150 m,
- proper control to 750 m,
- approximate orientation over 750m.

The most common distances are: the distance needed to safely stop before the obstacle, the distance needed to safely overtake on the two-lane two-way roads and distance and field of view when passing through the intersection. It is important that during daytime the perception in all this distances concern whole space in front on the vehicle but also for sides in significant angle.

The minimum distance in which driver absolutely shall recognize object is the stopping distance which is strongly dependent on vehicle speed. The maximum allowed speed differs between countries but is usually about 80-100km/h for country roads and 120-140 km/h (or more) for motorways. It means stopping distance from about 100m to nearly 200m (or more).

At the time when type approval requirements were firstly prepared for Europe (UN ECE Regulation) it was decided that vehicle illumination system will consist of passing beam and driving beam [2]. The idea of passing beam was that in area where can be present oncoming driver eyes the illumination should be reduced. This caused selection two parts of passing beam separated by cut-off line: the bottom part "light" and top part "shadow". As was mentioned above the headlights illumination allow for significantly weaker perception than during daytime because of technical possibilities of headlamps mounted on vehicle. In fact only driving beam allow for partially proper control (illuminated distances from 100m to 400m). Unfortunately passing beams are much more frequent used because of traffic condition. They usually allow for much shorter road illumination. In optimal situations it is around 100m to 150m. But much often - as will be shown - only 20m to 50m. Moreover the relatively intensive illumination is delivered to areas close to vehicle only. It cause the perception significantly impaired comparing daytime situation.

III. POSSIBILITIES OF HEADLAMP DESIGN AT THE TIME OF INTRODUCTION UN ECE REGULATIONS

As was mentioned above headlights illumination allow for significantly weaker perception because of technical possibilities of headlamps mounted on vehicle.

In historical terms, the present-day headlamp concept emerged before World War II but the first legal regulation of this issue in the European market appeared as late as in 1958. Important base for creation of requirement were technical possibilities of headlamp design and photometric measurements. The only known headlamp design was that time paraboloidal reflector equipped with two-filaments low voltage incandescent bulb (Fig.1., Fig.2).

Figure 1. Paraboloidal design of headlamp.

Figure 2. Incandescent double filament bulb.

A good point of the paraboloidal headlamp design was the fact that the light emitted from the source (a short filament of a low-voltage incandescent lamp) was formed as an almost-parallel light beam even if the filament position slightly differ from that of the focal point. Moreover, the manufacturing of such a reflector was not difficult because it was made by press-forming of a sheet-metal blank on a die, the shape of which was obtained by rotation of a segment of parabola. The drawpiece thus made was then metalized. The reflector calculations were also relatively simple, which was important in those days when relatively inexpensive and fast computers did not exist. The light beam was finally formed by a grooved (specially profiled) glass lens with prism-like elements that diffused the light.

This kind of headlamp design has relatively restricted possibility of beam pattern differentiation. Location of driving beam filament in optical focus allowed to produce nearly parallel beam which served as driving beam. Filament for passing beam was slightly shifted causing defocusing and divergence of light rays. The headlight cut-off was obtained by metal shield placed under passing beam filament.

The freedom of shaping the beam pattern was limited by the necessity of spreading a part of the luminous flux in the horizontal plane and directing a significant part of the flux to the place of the anticipated maximum luminous intensity (areas close to the type-approval test points 50R and 75R)[2]. The luminous flux of the bulb, subject to manufacturing and energy limitations, was additionally reduced by the shield. Otherwise it would be reflected by the lower reflector part towards the eyes of oncoming drivers (above the horizon) causing glare. Slightly differently it was done in American headlighting system without cut-off and without shield inside the bulb.

There was decided that incandescent bulb will be replaceable and separate requirements were set to the geometrical features of filament and to the it's luminous flux. In connection with headlamp features this intended to ensure repeatability of beam pattern after bulb change. As easy to imagine it strongly depend on tolerances of both elements and their optical interactions. Finally the intentions were realized only partially.

Since the paraboloidal design was subject to many limitations and the luminous flux distribution could be considered predictable and relatively repeatable. In such situation probably was decided that checking at several characteristic points and areas would be sufficient for ensuring the minimum required illuminance values in the entire area of interest (the road surface ahead of the vehicle). The other problem to solve was the possibility to do measurements of such beam pattern. Detailed scanning of whole beam pattern was impossible because of possibilities of photometric devices. In use were selenium cells with low sensitivity and response time. Also there were no computers of appropriate calculating power as well as computer digitally controlled goniometric mechanisms. In fact the only reliable and repeatable measurement method was manual measurements of beam pattern in long enough darkroom on surface of vertical screen with drawn lines and points.

IV. MATHEMATICAL MODEL OF HEADLIGHTS ILLUMINATION

For today it is very popular way of comparing beam pattern quality by use plots of isolux lines of vertical illumination at the road surface [4]. It is assumed that the same level of illuminance is responsible for object recognition. It is not true also for daytime but by high illumination levels it can be assumed that in distances important for decision making (a mentioned above 100m to 200m from obstacle) angular size of most obstacles are big enough to complete human observing, thinking, and decision making process. For low level of illuminance additionally it is important luminance threshold level connected with angular size of object, luminance and contrast - if background is not completely black. This is generally nonlinear relation but for this task the ratio of solid angle and luminance can be good simplification of criterion to be noticed.

Relations between important elements participating in headlights illumination are presented in Fig.3.

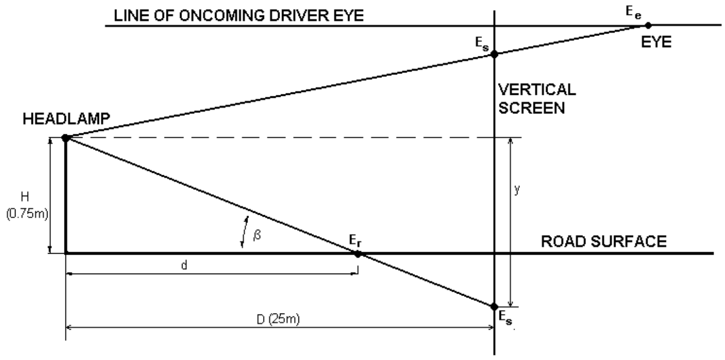

Figure 3. Relation between main elements in headlighting.

The photometric requirements were based on illumination of vertical screen which is positioned perpendicularly to the optical axis of headlamp.

Vertical position on the screen **y** equivalent to road distance d can be calculated:

$$y = -0.75 \cdot 25/d = -18.75/d \quad (1)$$

Relation between vertical screen illumination at the road surface vertical illumination is described by formula:

$$E_s \approx E_r \cdot d^2 / D^2 \quad (2)$$

Where:

H - mounting height of headlamp (0.75m);

y - vertical position of point on the measuring screen;

E_s - vertical illumination at 25m screen;

E_r - vertical illumination at 25m at the road surface;

d - distance from headlamp to object (at the road);

D - distance from headlamp to the screen (25m);

β - illumination angle.

Similarly is described illumination at the eye of oncoming driver.

$$E_e \approx E_r \cdot d^2 / D^2 \quad (3)$$

E_e- vertical illumination at eye of oncoming driver;

In Fig.4. is presented relation (1). It is easy to see highly nonlinear character of it when people assessing light at screen tends to treat it as directly proportional to the road condition.

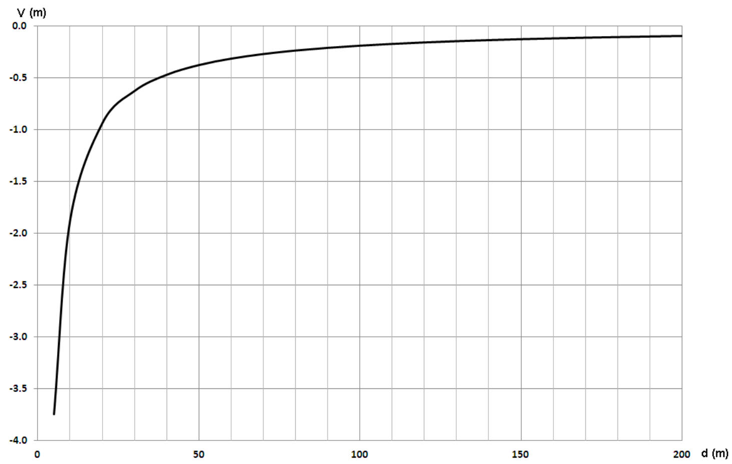

Figure 4. Relation between road distance and vertical position on measuring screen .

In Fig.5. is presented relation (2) for fixed road illumination of 5 lx.

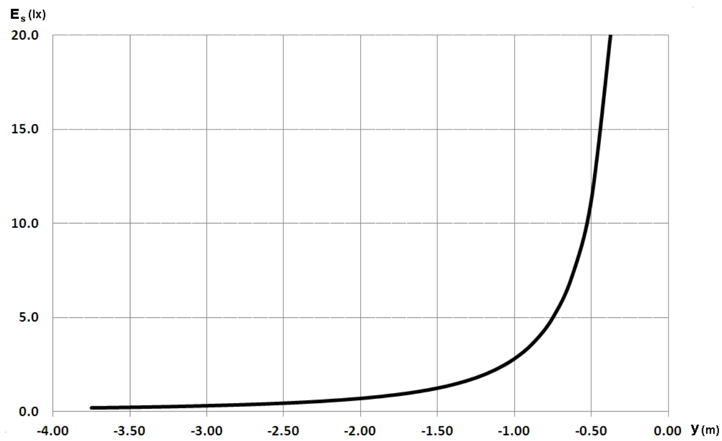

Figure 5. Relation between road distance and vertical position on measuring screen .

It is also very nonlinear relation. Despite this for screen areas are defined fixed illumination requirements (see below). Finally people assessing light at screen tends to treat it as reflecting the road condition.

V. PRINCIPLE OF ECE PASSING BEAM REQUREMENTS DEFINITION

In Fig.6. is presented screen for photometric measurements [2] and in Tab.1. this original requirements.

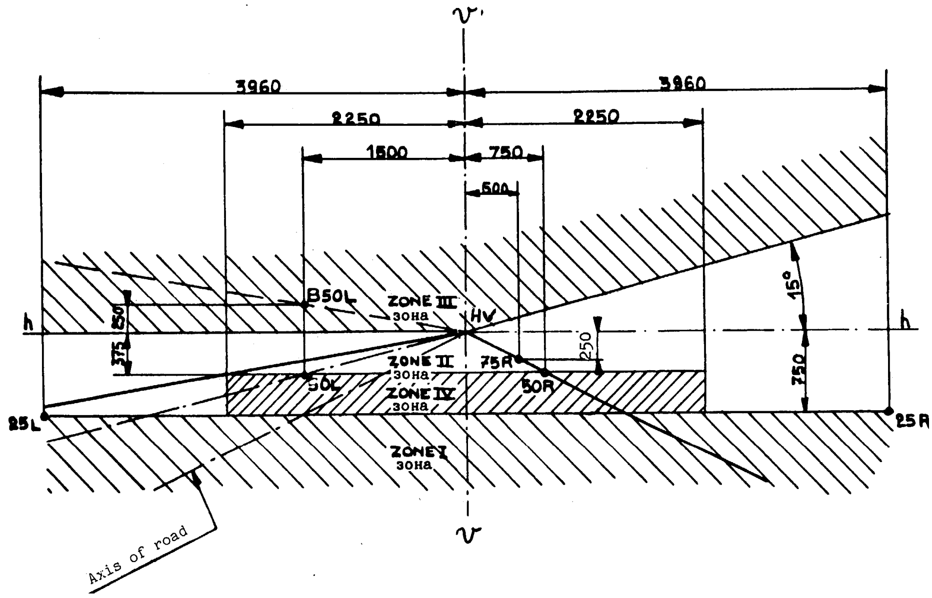

Figure 6. 25m measuring screen points and zones [2].

TABLE I. PHOTOMETRIC REQIREMENTS FOR FIRST HEADLIGHTS REGULATION [2].

Point on measuring screen		Required illumination in lux
Headlamps for right-hand traffic	Headlamps for left-hand traffic	
Point B 50 L	Point B 50 R	≤ 0.4
" 75 R	" 75 L	≥ 6
" 50 R	" 50 L	≥ 6
" 25 L	" 25 R	≥ 1.5
" 25 R	" 25 L	≥ 1.5
Any point in zone III		≤ 0.7
" " " " IV		≥ 2
" " " " I		≤ 20

For the first regulation [2] the minimum required value in point 75R was 6lx @ 25m for nominal filament flux at 12V. By real voltage (13,2) it is around 50% more. For two headlamps it means 2 lx at the road surface. The same value set on screen for point 50R(12lx) means 4 lx. Because 75R and 50R are close on screen the same required screen value can be justified by relatively uniform light distribution by paraboloidal design. Contemporary headlamp designs can offer high illumination just under cut-off which decrease downwards the screen.

Similar value was required in points 25L and 25R (2x1.5 l x 1.5 = 4.5 lx). Slightly less value was required in zone IV (2x2lx@25mx 1.5 for 50m =1.5 lx).

When we assume above values and take into account averaged value we can approximate expected ideal value in relation to vertical axis of measuring 25m screen as presented in Fig.5.

For passing beam is assumed reduction of illumination above horizon and presence of cut of-line. Therefore for passing beam the illumination over y=-0.25m should decrease.

For driving beam general expected tendency is similar but is no restriction over horizon. But restriction arise because of limited filament flux (700lm for R2 bulb by 12V). Also for good visibility it is important to have light higher, over horizon an lower because road is not flat and load influences the real beam pattern axis angle.

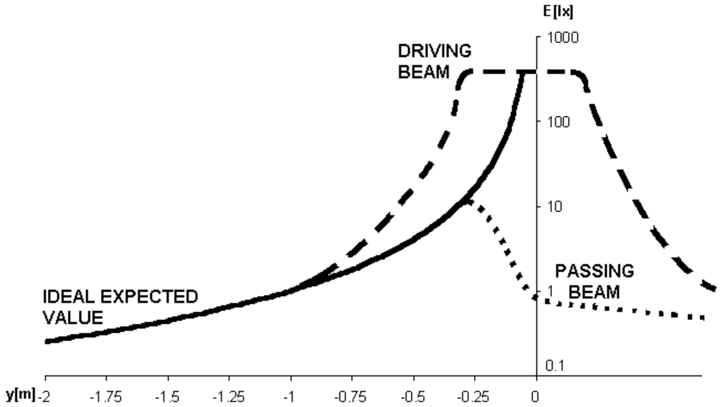

Figure 7. Ideal characteristics for road illumination, passing and driving beam.

The relation of the measuring screen to the real road panoramic view is shown in Fig.6. It is easy to see that it is assumed straight road without curves as well as highs and lows of terrain.

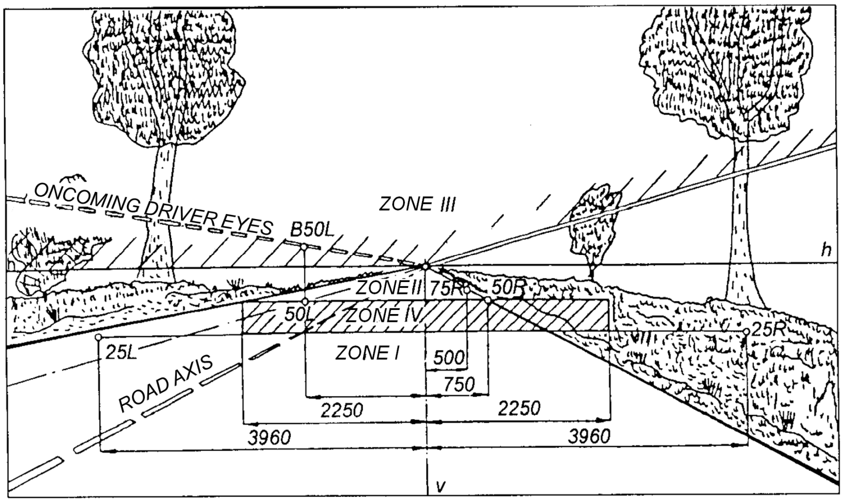

Figure 8. 25m measuring screen points and zones in relation to the road [3].

Type approval requirements were simplified because of features of paraboloidal headlamp. Variations of illumination inside beam pattern were significantly restricted. Rays are slightly dispersed by paraboloidal reflector in relation to parallel because unfocused filament - there are two filaments and only one can be in focus. In horizontal direction it is advantage but in vertical a lot of flux is directed too low, close to the vehicle and finally lost. Glass with rifled lens only partially can change direction of rays and concentrate them in area close to 75 and 50R measuring points. In such situation there was no reason to make special minimum requirements in ZONE I. But it was restricted by maximum value (20 lx), because "natural" paraboloidal headlamp tends to deliver excessive values close to the vehicle. Additionally the minimum requirements were set to 25L and 25R points to guarantee some illumination on sides. By such requirements dispersion of light for sides by rifles guaranteed whole background illumination. The principle of operation and example of paraboloidal design are shown in Fig. 9.

Figure 9. Schematic and beam pattern example of paraboloidal headlamp design with shielded filament. It cause relatively uniform illumination in whole part of screen under cut-off and only some additional light close to needed maximums (50R, 75R)

All above described simplifications, however, was additionally justified by the capabilities of the measuring equipment available at that time. The photo-element (e.g. a selenium cell) had to be relatively large (with a diameter of about 60 mm) for adequate sensitivity and correction of spectral-response characteristic to be obtained. It was moved manually against the background of the "measuring" screen, which was situated in darkroom at the distance of 25 m from the headlamp tested and was illuminated by the light beam emitted by the headlamp.

VI. INSTALATIN ON THE VEHICLE

In component regulation [2] are prescribed values for screen. There were assumed fixed mounting height of headlamp (0.75m) and initial aiming (1.0% down). Light distribution was described above. But real road illumination depend on real mounting height at the vehicle and cut-off inclination. There was allowed relatively big range of mounting heights of headlamp from 0.5 m to 1.2 m and up to 1.5 m for special vehicles. If aiming of headlamp would be not adapted to mounting height the road illumination would change regarding nominal position. Moreover the quantity and load distribution on the vehicle change inclination of longitudinal axis and, finally, the angle of cut-off. In installation regulation [5] there were described required tolerances of cut-off inclination in relation to mounting height (Fig.8.).

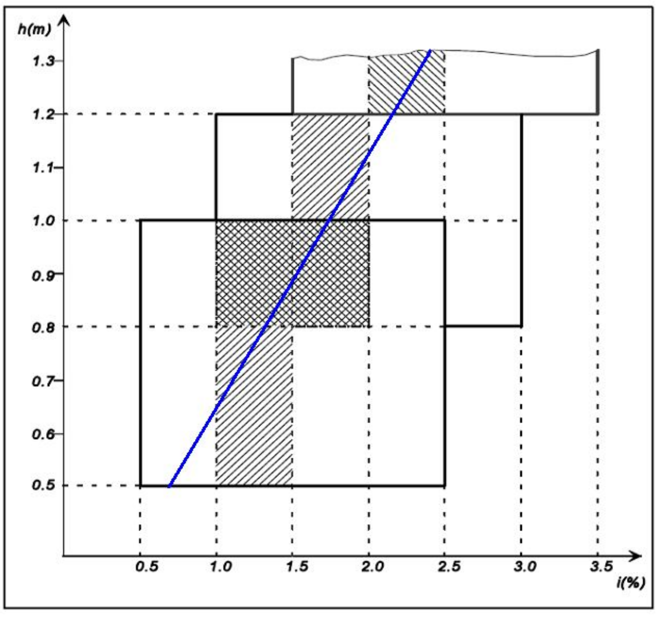

Figure 10. Requirements for cut of position (I) in dependence on mounting height (h) in [5]. Blue line represents cut-off crossing with road surface at 75 m in front of the vehicle.

We can see that there are relatively big ranges for initial aiming, leveling tolerances and mounting heights. To obtain the road illumination as defined in component regulation [2] it is needed that relation between mounting height an cut-off inclination should be linear function crossing 0,0 point (Fig.11.) - compare Fig. 3 and (1). The simplest way to define repeatable and unambiguous road illumination distance is the distance where cut-off cross road surface (also 75R point). For nominal aiming of component requirements it is 75m. But extreme values of tolerances [5] differs many times from that value. This reflect adjustment of requirements to "technology". For large ranges of height the production tolerances are the same. But in real road condition the road illumination distance can change from 20m (I=2.5%, h=0.5) to 200m (I=0.5%, h=1.0m) not including measurement and in use aiming inaccuracies. In Fig.11. is presented initial aiming and leveling tolerances rage which guarantee the same road illumination distance (50m to 100m with nominal 75m value) independently on mounting height [6].

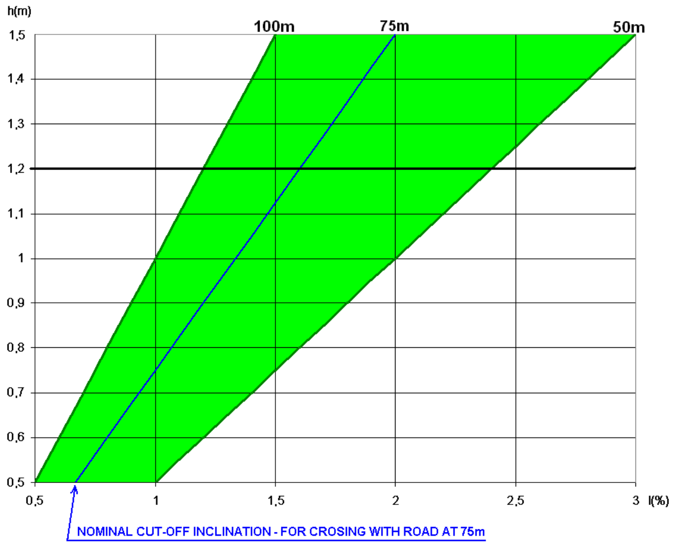

Figure 11. Requirements for cut of position (I) in dependence on mounting height (h) in [R 48]. Blue line represents cut-off crossing with road surface at 75 m.

Similarly can be analyzed glare area which was defined over horizon by (3). The only difference is that glare can occur in relatively big area. It was defined for zone III and for point B50L representing eye of oncoming driver at distance 50m. In fact it should be similarly defined for plane parallel to the road surface where the eyes can be present. It shold be also included distance which is nit fixed but change in way similar to the road surface.

VII. LIGHT SOURCE INFLUENCE

Besides headlight and installation requirements also exchangeable light sources requirements for first regulation were specified. For type approval measurements were used etalon bulbs of narrowed tolerances. The mass production tolerances were to be compensated on aiming way. This was also significant simplification but general analyze in configuration with paraboloidal design calculations were relatively simple. Finally the beam pattern measured at the screen can be subject of above described mathematical model and simplifications result.

VIII. PRESENT TECHNOLOGY SITUATION AND CONCLUSIONS

As was shown the way of defining photometric requirements was very simplified regarding real needs of road illumination. By nearly 60 years of using this kind of requirement there were introduced many different new light sources an headlamp designs. For these reasons there were introduced new regulations. But the only significant changes in comparison to first one was introducing higher required values and addition of some more points, segments and zones. The general rule to describe photometric requirements at the vertical screen remain unchanged. But many contemporary solution allow for much more precise and effective directing light to the road. As result presently the road often can be illuminated much better than required minimum values. The another weak point still aiming/leveling provision which remain unchanged and for really good beam pattern allow for significant deterioration of their performance. There is required automatic leveling for light source with flux more than 2000 lm but tolerances of leveling were left unchanged. Finally the quality of road illumination can change in very big range from one vehicle to another as well in the same vehicle under (manual or automatic) change of leveling.

From this point of view is need to improve the way of defining requirement. Present measuring devices e.g. computer controlled scanning photogoniometers allow for relatively quick and accurate measurements of headlamps with much better resolution and accuracy than many years ago. It is also commonly used by manufacturers and laboratories to represent the road illumination by plots of isolux lines of vertical illumination at the road surface.

This method should be adopted to describe contemporary requirements for type approval because outdated system of screen requirements from one side allow for relatively low quality of illumination from the other the simplifications valid for paraboloidal design are not valid for contemporary design especially for multiunit and LED designs. Example of proposed requirements for equivalent contemporary halogen headlamps id presented in Fig. 12.

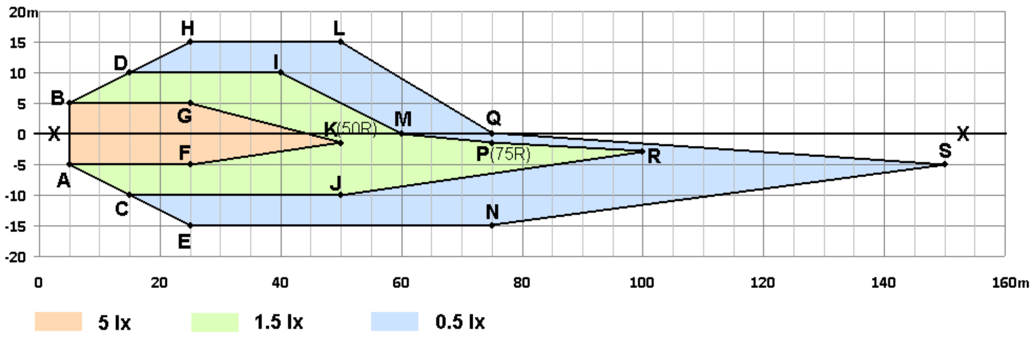

Figure 12. Proposed minimum requirements for headlamp defined for road surface reflecting present halogen possibilities level.

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