REQUIREMENTS ANALYSIS FOR PROVIDING ADEQUATE ARTIFICIAL ILLUMINATION IN OPERATIONAL AREAS DURING EMERGENCY RESPONSE TO ROAD TRAFFIC ACCIDENTS

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АНАЛИЗ НА ИЗИСКВАНИЯТА ЗА ОСИГУРЯВАНЕ НА НЕОБХОДИМАТА ИЗКУСТВЕНА ОСВЕТЕНОСТ НА РАБОТНОТО МЯСТО ПРИ ОТСТРАНЯВАНЕ НА АВАРИИ И КАТАСТРОФИ С МОТОРНИ ПРЕВОЗНИ СРЕДСТВА

Abstract

Artificial lighting is a critical factor for the safety and effectiveness of rescue teams operating under reduced visibility – at night, in fog, smoke, rain, or snow. The paper analyses the main Bulgarian regulations and international standards related to workplace and emergency lighting and compares their quantitative requirements. On this basis, physiological constraints of human vision (visual sensitivity, adaptation time, contrast sensitivity and fatigue) are discussed. Elementary photometric relations between luminous flux, illuminance, luminous intensity and uniformity are introduced, together with a simple example of illuminance calculation for a typical accident scene. The analysis shows a clear discrepancy between detailed international requirements (100–200 lx and above, with defined uniformity criteria) and the lack of explicit minimum illuminance levels in the Bulgarian regulatory framework. Recommendations are formulated for the development of national guidance on artificial lighting during emergency response to road traffic accidents.

Keywords: *Artificial Lighting; Workplace; Rescue Teams; Traffic Accidents.*

INTRODUCTION

Road traffic accidents (RTAs) are among the leading causes of trauma and loss of human life in contemporary society. They result in substantial human, material and social losses and require a rapid and well coordinated emergency response [1]. A particularly worrying fact is that a significant share of occupational accidents among personnel of the General Directorate Fire Safety and Civil Protection (GDFSPC–MoI) occur precisely during firefighting and rescue operations [2], [3].

A considerable proportion of RTAs occur under reduced visibility – at night, in fog, smoke, rain or snowfall. Under such conditions adequate artificial illumination is a key factor for the safety and effectiveness of rescue teams. Insufficient illuminance leads to delayed reactions, errors when operating specialized tools, difficulties in locating and evacuating casualties, and an increased risk of secondary incidents.

The existing Bulgarian regulatory framework describes in detail personal protective equipment and protective clothing for firefighters [4], as well as general requirements for healthy and safe working conditions at workplaces [5]. However, it does not contain a dedicated document focused on the provision of artificial illumination during road side emergency and rescue activities.

The aim of this paper is to analyse and systematize the requirements for ensuring adequate artificial illumination during mitigation of incidents and crashes involving motor vehicles by:

- reviewing the national regulatory framework and internal documents related to lighting in emergency environments [5], [6], [7], [8];
- comparing foreign standards and technical guidelines for emergency and work site lighting [9], [10], [11], [12], [13], [14], [15], [16];
- analysing physiological constraints of human vision under low illumination conditions [17], [18], [19], [20], [21], [22];
- introducing elementary lighting engineering relations and example calculations applicable when planning illumination of the operational area [23], [24], [25], [26].

1. Regulatory Requirements in the Republic of Bulgaria for Artificial Lighting at RTAs

In Bulgarian legislation there is no specialized, comprehensive act that explicitly regulates artificial illumination of the workplace during mitigation of RTAs. Nevertheless, provisions that partially address lighting in emergency environments and the use of lighting equipment are scattered across several documents.

1.1. General requirements for workplaces and electrical installations

Ordinance No. 7 of 23 September 1999 on minimum requirements for healthy and safe working conditions at workplaces and during the use of work equipment [5] requires that outdoor workplaces be additionally illuminated by artificial lighting when natural light is insufficient. The ordinance explicitly states that for workplaces or activities with specific lighting requirements special norms shall be applied. Given the nature of emergency rescue work, one may reasonably expect the existence of such specialized norms, but they have not been developed for RTAs.

Ordinance No. 3 of 9 June 2004 on the structure of electrical installations and power lines [6] is the main national technical document defining requirements for stationary and outdoor electrical installations. It partially regulates work with luminaires in emergency conditions, but contains no provisions directly applicable to temporary rescue operations at accident scenes.

The Road Traffic Act [8] regulates lighting systems for roads and vehicles, but does not address in detail the illumination of operational zones during rescue operations.

1.2. Internal documents of GDFSPC–MoI

Two internal documents of the General Directorate Fire Safety and Civil Protection (GDFSPC–MoI) touch on the provision of artificial illumination at workplaces during mitigation of incidents and crashes involving motor vehicles.

An internal Instruction indirectly introduces a classification of lighting devices used within GDFSPC–MoI. According to the number of users, lighting devices are divided into:

- **individual**, and
- **group** devices.

Individual lighting devices are subdivided into:

- portable hand lamps, and
- helmet mounted lamps.

Group lighting devices include:

- vehicle mounted stationary floodlights on specialized vehicles, and
- motorized lighting devices.

Equipment tables in the Instruction specify the mandatory lighting devices with which vehicles and personnel must be equipped. For firefighting and rescue vehicles one or two group devices are required depending on total vehicle weight, level of equipment and technical parameters. The specialized vehicles most frequently used at RTAs include:

- medium firefighting vehicles – equipped with two group lighting devices;
- rapid intervention rescue vehicles for RTAs – equipped with one group lighting device;
- general purpose rescue vehicles – equipped with two group lighting devices.

Regarding individual lighting devices, the Instruction requires portable hand lamps for members of the incident command staff and duty officer, and helmet mounted lamps for members of medical and rescue teams. No concrete photometric parameters or performance requirements (luminous flux, illuminance, autonomy, ingress protection rating, colour temperature, etc.) are specified.

Specific requirements concerning illumination of the accident scene during rescue operations carried out by GDFSPC–MoI staff are laid down in Order No. Iз 1775 of 05.08.2010 on approving the Rules for health and safety at work for fire safety and rescue personnel [7]. This is the only national document that directly includes instructions on lighting during fires and emergencies. It states that the accident site shall be illuminated by stationary floodlights on the firefighting/rescue vehicle, portable lighting devices, electric hand lamps and others, under the following conditions:

- floodlights shall be arranged so as to illuminate all working areas without dazzling personnel;
- priority shall be given to illuminating paths used for rescuing people;
- cables shall not be routed through areas where they may be damaged by fire or debris, or obstruct evacuation and deployment [7].

The only explicit technical requirement is the supply voltage of portable lighting devices:

- portable floodlights and other luminaires with power above 250 W – not more than 220 V;
- portable floodlights and luminaires with power up to 250 W – up to 36 V;
- for floodlights with voltage above 36 V a three core cable shall be used, with one core serving as protective earthing conductor.

The Order also sets requirements for personnel operating lighting equipment:

- they must be trained to work with lighting devices;
- they must not allow the use of non standard or defective equipment;
- operation, maintenance and inspection shall follow the manufacturer's instructions;
- the serviceability of lighting devices shall be checked periodically and after each use;
- operation of generators and machines that are not earthed, as well as leaving them running without supervision, is prohibited;

- at the end of work or when additional supply lines are laid, voltage shall be switched off; in case of short circuit or other fault, work shall be suspended until the fault is eliminated [7];
- supply cables must be securely connected to lamp and floodlight housings, with measures against excessive mechanical stress (pressure, bending, stretching, etc.).

The analysis shows that the Bulgarian regulatory framework does not provide complete and concrete regulation of artificial lighting during mitigation of RTAs, nor does it define clear values of required illuminance. Existing documents contain only partial technical requirements related to the safe use of lighting equipment in emergency environments. Flashlights and portable lighting devices are recognized as necessary and acceptable, but there is no unified standard specifying their characteristics, brightness, operating time or robustness. This underscores the need to develop a national standard or methodological guideline that would regulate in detail the illuminance of the workplace during rescue actions on the road.

2. Requirements for Illuminance According to Foreign National Standards

In contrast to the Republic of Bulgaria, a number of countries have introduced specific quantitative requirements for illuminance that aim to ensure safety and operational effectiveness.

2.1. Australia

In Australia, recommended illuminance levels for work and emergency zones – generally in the range 100–200 lx – are defined primarily in occupational safety rules and guidelines for temporary and emergency work areas [13], [22]. These levels are considered sufficient for safe movement, hazard identification and performance of rough to moderately precise tasks.

2.2. Canada

In Canada, requirements are contained in the Canada Occupational Health and Safety Regulations (SOR/86 304), Part VI "Lighting", Schedule III [9], [14]. The objective is to guarantee safe movement and work in both industrial and emergency conditions.

Temporary escape routes and paths used by evacuation flows or vehicles must be illuminated to 50–100 lx depending on traffic intensity. In practice this is achieved using portable LED floodlights with adjustable output mounted on telescopic stands, which can be positioned flexibly by rescue teams [14].

2.3. United States

The U.S. regulatory framework for lighting at RTAs is an integrated system of recommendations and binding requirements. The main documents – FHWA MUTCD, NFPA 1900, OSHA 29 CFR 1910 and IES DG 26 16 – jointly cover temporary lighting of road work and emergency zones as well as the built in work lighting systems of fire and rescue vehicles:

- **FHWA MUTCD, Part 6** defines an illuminance range of approximately 54–215 lx depending on task type, ensuring safe movement and precise operations in road work and emergency zones [10], [17];
- **NFPA 1900** requires 20–30 lx in critical workspaces around the vehicles, providing uniform and safe lighting for loading, unloading and rescue operations [11], [20];
- **OSHA 29 CFR 1910** specifies illuminance levels from 54 lx up to 320 lx for general and specialized workplaces, including first aid and medical stations [12], [21];
- **IES DG-26-16** supplements these standards with engineering guidelines on lighting design and uniformity, recommending 20–100 lx in the areas around RTAs and rescue equipment with control of glare and uniformity [16], [23].

Taken together, these documents provide not only numerical illuminance values but also technical criteria for uniformity, mounting heights, light distribution and colour rendering. This enables an optimal balance between visibility, safety and speed of response while minimizing secondary risks.

2.4. Japan

The Japanese standard JIS Z 9110:2010 "General rules of recommended lighting levels" contains a detailed classification of work tasks and corresponding illuminance levels [14], [18]. Emergency operations at RTAs (placing cones, inspecting vehicles, working with medical equipment) belong mainly to Group III – "general tasks". For this group the standard requires a minimum average illuminance of E_{avg} ≥200 lx, in order to guarantee sufficient visual comfort and reaction speed [14].

In addition, the standard imposes a uniformity requirement: Emax/Emin ≤ 3:1, so as to avoid deep shadows within the working area [18].

2.5. International recommendations

International practice provides clearly measurable parameters for emergency lighting. Standards and guidelines regulate:

- minimum illuminance Emin;
- uniformity of illuminance;
- limitations on glare and requirements for colour rendering.

The CIE Standard 150:2017 "Lighting of Outdoor Workplaces" recommends for outdoor workplaces with increased risk (vehicle manoeuvring, work around moving traffic) illuminance between 50 and 200 lx and a minimum uniformity factor [15]:

$$U_0 = \frac{E_{\min}}{E_{\text{avg}}} \geq 0{,}4 \qquad (1)$$

In the Republic of Bulgaria similar quantitative requirements for emergency lighting at RTAs are currently absent, which leads to differing interpretations and inconsistent practices. This highlights the need to develop national rules for lighting the workplace at RTAs as a specific subset of the numerous activities performed by fire safety and civil protection structures.

Summary: While Bulgaria relies on scattered technical and operational documents that only partially address artificial lighting in RTA conditions, other countries have introduced targeted standards specifying illuminance levels in emergency zones. U.S., Canadian, Japanese and Australian regulations define clear ranges (typically 50–200 lx for general emergency activities and up to 300–500 lx for detailed medical or technical tasks), along with uniformity and glare limits. Compared to this, the Bulgarian framework remains undefined and dependent on the subjective judgement of individual teams.

3. SPECIFIC REQUIREMENTS ARISING FROM THE PHYSIOLOGY OF HUMAN VISION

3.1. Basic visual characteristics

The human visual system is the most heavily engaged sensory system during rescue operations, particularly in dynamic, unpredictable and stressful environments such as RTAs. The ability of the eye to detect, recognize, identify and localize objects determines the speed and effectiveness of response. At the same time vision is strongly dependent on environmental illuminance: physiological thresholds of perception constrain performance at low light levels [17], [25].

3.1.1. Luminous sensitivity of the eye

The human retina contains two main types of photoreceptors – cones and rods:

- **Rods** are highly sensitive at low light levels and are responsible for scotopic (night) vision, but provide no colour information. They function effectively at illuminances below about 10 lx [20];
- **Cones** operate in photopic (daylight) vision – typically above 100 lx – and provide colour discrimination and high spatial resolution [20], [24].

At low illuminance the limitations of the visual system manifest as loss of colour precision, reduced contrast and decreased ability for detailed analysis. This is critical when working with casualties, fine tools and situations where small visual details determine the choice of action [1].

3.1.2. Adaptation time

Visual adaptation to changes in illuminance is a two stage process:

- **Dark adaptation** begins quickly but full activation of rods is achieved after 20–30 minutes; visual efficiency is low during the first 5 minutes [16], [20];
- **Light adaptation** proceeds faster (within 2–3 minutes), yet sudden increases in illuminance may cause temporary glare and loss of contrast [19].

At incidents in tunnels, underpasses or unlit rural locations, where lighting is irregular or fluctuating (headlamps, flashing lights, portable floodlights), visual adaptation is often incomplete, increasing the risk of disorientation and delayed actions [27].

3.1.3. Contrast sensitivity and object recognition

The eye perceives shapes and objects through contrast – the difference between luminance of the object and its background. Under reduced illuminance:

- the ability to distinguish dark objects against dark backgrounds (e.g. a casualty on asphalt) can decrease by up to 60%;
- the capacity to detect small objects (smaller than 20 mm) decreases markedly;

- recognition of faces, movements and hands becomes difficult at illuminances below about 20 lx [13], [18], [24].

These effects are critical when working with cutting and hydraulic tools, where accuracy and safety depend on clear visual separation of objects.

3.1.4. Physiological threshold of perception

Experimental and practical data indicate that [15], [20], [28]:

- at $E<5$ *lx* only coarse contours are perceived, without reliable colour or depth information;
- at $E\approx10–30$ *lx* orientation and movement are possible, but visual errors are frequent;
- at $E\approx100$ *lx* cones become dominant and perception improves substantially;
- at $E\approx300$ *lx* and above the full capacity for detailed colour vision and depth perception is achieved.

These limits define threshold values of environmental illuminance below which rescue actions become inefficient and risky [15].

Studies of **Relative Visual Performance (RVP)** show that visual performance increases approximately logarithmically with illuminance [27], [28]:

$$\mathrm{RVP} \sim \log_{10} E \tag{2}$$

with a steep drop below about 50–100 lx [27].

3.1.5. Effects of fatigue and stress

Psychophysiological research demonstrates that [21], [22]:

- under fatigue and stress the visual detection threshold may increase by up to 40%;
- even at normal illuminance levels visual quality decreases due to increased blink rate, reduced concentration and ocular dryness;
- in environments with smoke, thermal instability and noise significant visual disorientation is observed.

Summary: Physiological constraints of the visual system require particular attention when defining parameters for emergency lighting. The need for adaptive, zoned and sufficiently intense illumination arises directly from the limits of human perception, the realities of the incident environment and the psychophysical condition of rescuers. Defining concrete illuminance values in the operational area must therefore be directly linked to these biological limits and to the requirement for maintaining maximum effectiveness in critical situations.

4. Photometric Relations Applicable at RTAs

Studies on nominal artificial illuminance of workplaces show that properly selected and configured lighting parameters are crucial for safety, speed and quality of work, especially in critical situations such as RTAs. Photometric quantities – luminous flux, intensity, illuminance, luminance and spectral characteristics – cannot be considered in isolation from the physiology of human vision [23], [24], [25], [26].

4.1. Basic quantities:

- **Luminous flux Φ** [lm] – total quantity of light emitted by a source;
- **Luminous intensity I** [cd] – luminous flux emitted in a given direction per unit solid angle;
- **Illuminance E** [lx] – luminous flux incident on a unit area:

$$E = \frac{\Phi}{S} \tag{3}$$

where S is the illuminated area [m²];

- Luminance – subjective perception of the "brightness" of a surface; in emergency lighting it is controlled indirectly by limiting glare [15], [23].

4.2. Illuminance from a point

When a floodlight may be approximated as a point source (sufficient distance to the illuminated plane), the illuminance at a point on the plane can be estimated as:

$$E = \frac{I\cos\theta}{r^2} \tag{4}$$

where:

- I is the luminous intensity in the relevant direction [cd];
- r is the distance from the source to the point [m];
- θ is the angle between the surface normal and the direction of the light beam.

For a point directly beneath a floodlight mounted vertically above the working area ($\theta \approx 0°$, $\cos\theta \approx 1$), the expression simplifies to:

$$E \approx \frac{I}{r^2} \tag{5}$$

Example. For a floodlight with luminous intensity $I = 20\,000$ *cd* mounted at height $r = 8$ *m*, the illuminance directly below it is:

$$E \approx \frac{20\,000}{8^2} = \frac{20\,000}{64} \approx 312{,}5 \text{ lx}.$$

which is sufficient for precise operations such as work with hydraulic tools and first aid [15], [23].

4.3. Maintenance factor and luminaire efficacy

Actual illuminance in an emergency environment is lower than theoretical values due to dirt on floodlights, atmospheric conditions, imperfect aiming, etc. For design purposes a **maintenance factor** $k_z > 1$ is introduced [24], [25]:

$$\Phi_{\text{req}} = E_{\text{req}} \cdot S \cdot k_z \tag{6}$$

where Φ_{req} is the required total luminous flux, E_{req} is the target illuminance and S is the illuminated area.

Typical values for outdoor workplaces are k_z=1,2–1,4 [24].

The luminous flux of a single floodlight can be roughly estimated from its electrical power P [W] and luminous efficacy η[lm/W]:

$$\Phi_{\text{lamp}} \approx P \cdot \eta \quad (7)$$

For modern LED floodlights, η is commonly in the range 100–150 lm/W [23], [24].

4.4. Illuminance uniformity

For safe work not only the average illuminance but also its spatial distribution is important. International standards introduce a **uniformity factor** [14], [15]:

$$U_0 = \frac{E_{\min}}{E_{\text{avg}}}.$$

CIE 150:2017 recommends for outdoor workplaces U0 ≥ 0,4 [15], while JIS Z 9110:2010 requires:

$$\frac{E_{\max}}{E_{\min}} \leq 3,$$

which effectively limits harsh shadows [14], [18].

Example. If in the operational area we measure:

E_{avg} =150 lx;
E_{min} =90 lx;

then:

$$U_0 = \frac{90}{150} = 0,6 > 0,4,$$

so the uniformity requirement is satisfied.

5. Example Illuminance Calculation for an RTA Scene

To illustrate practical requirements, consider a typical operational area around an RTA with approximate area S = 60 m2 (e.g. 20 m long and 3 m wide). The objective is to achieve an average illuminance:

$$E_{\text{req}} = 150 \text{ lx},$$

which lies within the 100–200 lx range recommended for emergency workplaces [9], [13], [15].

5.1. Determining the required luminous flux

Using the illuminance relation and a maintenance factor k_z=1,25, the required total luminous flux is:

$$\Phi_{\text{req}} = E_{\text{req}} \cdot S \cdot k_z = 150 \cdot 60 \cdot 1{,}25 = 11\,250 \text{ lm}.$$

If the rescue team has LED floodlights each providing approximately $\Phi_{lamp} \approx 4\,000\ lm$, the required number of floodlights is:

$$N = \frac{\Phi_{req}}{\Phi_{lamp}} = \frac{11\,250}{4\,000} \approx 2{,}8.$$

Since N must be an integer and is rounded up, **at least three floodlights** with similar characteristics are required, positioned so as to ensure the necessary uniformity $U_0 \geq 0{,}4$.

5.2. Consistency with physiological constraints

At an average illuminance $E_{avg} \approx 150$ lx:

- the visual system operates predominantly in the photopic regime – colour and detail perception are significantly better than at levels below 50 lx [20], [25];
- contrast sensitivity is sufficient for reliable detection of small details and assessment of surface defects [18], [19], [24];
- relative visual performance lies in the "plateau" of the logarithmic dependence RVP~$\log_{10} E$, supporting rapid and accurate actions [27], [28].

For tasks requiring even higher precision (e.g. detailed medical procedures), international practice allows local increases of illuminance to 300–500 lx achieved with additional task lighting [12], [23].

CONCLUSION

Artificial lighting is a critical factor for the safety and effectiveness of emergency rescue operations at motor vehicle crashes. While international standards clearly define minimum illuminance levels, uniformity and glare limits, Bulgaria still lacks a unified regulatory framework. Insufficient or inappropriate lighting poses a direct threat to the safety of both rescuers and casualties, increasing the likelihood of errors, slowing down operations and leading to fatigue and reduced concentration.

The analysis reveals a pronounced discrepancy between international practice and the Bulgarian regulatory framework regarding artificial lighting during emergency operations at RTAs. In the U.S., Canada, Japan and Australia concrete illuminance levels are specified – typically 50–200 lx for general emergency activities and up to 300–500 lx for precise tasks – together with uniformity requirements and technical criteria for luminaires [9], [10], [11], [12], [13], [14], [15], [16], [18], [23]. In Bulgaria, by contrast, Ordinance No. 7 [5], Ordinance No. 3 [6], Order No. Iз 1775 [7] and the Road Traffic Act [8] address lighting only indirectly and do not provide objective criteria for planning and assessing illuminance in the operational area.

Physiological analysis shows that at illuminances below 30–50 lx human vision operates with limited contrast sensitivity, elevated perception thresholds and increased risk of errors, especially under stress [18], [19], [20], [21], [22], [25]. Basic lighting engineering calculations demonstrate that to achieve the recommended 100–200 lx on a typical operational area, 2–3 modern LED floodlights with total luminous flux on the order of 10,000–15,000 lm are required, positioned to ensure satisfactory uniformity [15], [23], [24].

There is an evident need for a comprehensive national strategy, including:

- development of a standard or methodological guideline specifying minimum illuminance levels and uniformity for mitigation of RTAs;
- updating equipment tables for firefighting and rescue vehicles to reflect quantitative lighting criteria;
- integrating training modules on lighting engineering and illuminance assessment into the preparation of GDFSPC–MoI personnel [28], [29], [30];
- systematic control and periodic testing of lighting equipment and generators.

Only by combining scientifically grounded norms, adequate technical solutions and targeted training of rescue teams can a high level of safety and effectiveness be ensured during mitigation of incidents and crashes involving motor vehicles [26].

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