



International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

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Descriptor: Lighting. Illuminating engineering
Descriptor: Photometry

THE INTERNATIONAL COMMISSION ON ILLUMINATION

The International Commission on Illumination (CIE) is an organization devoted to international co-operation and exchange of information among its member countries on all matters relating to the art and science of lighting. Its membership consists of the National Committees in about 40 countries.

The objectives of the CIE are:

1. To provide an international forum for the discussion of all matters relating to the science, technology and art in the fields of light and lighting and for the interchange of information in these fields between countries.
2. To develop basic standards and procedures of metrology in the fields of light and lighting.
3. To provide guidance in the application of principles and procedures in the development of international and national standards in the fields of light and lighting.
4. To prepare and publish standards, reports and other publications concerned with all matters relating to the science, technology and art in the fields of light and lighting.
5. To maintain liaison and technical interaction with other international organizations concerned with matters related to the science, technology, standardization and art in the fields of light and lighting.

The work of the CIE is carried out by Technical Committees, organized in seven Divisions. This work covers subjects ranging from fundamental matters to all types of lighting applications. The standards and technical reports developed by these international Divisions of the CIE are accepted throughout the world.

A plenary session is held every four years at which the work of the Divisions and Technical Committees is reported and reviewed, and plans are made for the future. The CIE is recognized as the authority on all aspects of light and lighting. As such it occupies an important position among international organizations.

LA COMMISSION INTERNATIONALE DE L'ECLAIRAGE

La Commission Internationale de l'Eclairage (CIE) est une organisation qui se donne pour but la coopération internationale et l'échange d'informations entre les Pays membres sur toutes les questions relatives à l'art et à la science de l'éclairage. Elle est composée de Comités Nationaux représentant environ 40 pays.

Les objectifs de la CIE sont :

1. De constituer un centre d'étude international pour toute matière relevant de la science, de la technologie et de l'art de la lumière et de l'éclairage et pour l'échange entre pays d'informations dans ces domaines.
2. D'élaborer des normes et des méthodes de base pour la métrologie dans les domaines de la lumière et de l'éclairage.
3. De donner des directives pour l'application des principes et des méthodes d'élaboration de normes internationales et nationales dans les domaines de la lumière et de l'éclairage.
4. De préparer et publier des normes, rapports et autres textes, concernant toutes matières relatives à la science, la technologie et l'art dans les domaines de la lumière et de l'éclairage.
5. De maintenir une liaison et une collaboration technique avec les autres organisations internationales concernées par des sujets relatifs à la science, la technologie, la normalisation et l'art dans les domaines de la lumière et de l'éclairage.

Les travaux de la CIE sont effectués par Comités Techniques, organisés en sept Divisions. Les sujets d'études s'étendent des questions fondamentales, à tous les types d'applications de l'éclairage. Les normes et les rapports techniques élaborés par ces Divisions Internationales de la CIE sont reconnus dans le monde entier.

Tous les quatre ans, une Session plénière passe en revue le travail des Divisions et des Comités Techniques, en fait rapport et établit les projets de travaux pour l'avenir. La CIE est reconnue comme la plus haute autorité en ce qui concerne tous les aspects de la lumière et de l'éclairage. Elle occupe comme telle une position importante parmi les organisations internationales.

DIE INTERNATIONALE BELEUCHTUNGSKOMMISSION

Die Internationale Beleuchtungskommission (CIE) ist eine Organisation, die sich der internationalen Zusammenarbeit und dem Austausch von Informationen zwischen ihren Mitgliedsländern bezüglich der Kunst und Wissenschaft der Lichttechnik widmet. Die Mitgliedschaft besteht aus den Nationalen Komitees in rund 40 Ländern.

Die Ziele der CIE sind:

1. Ein internationales Forum für Diskussionen aller Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik und für den Informationsaustausch auf diesen Gebieten zwischen den einzelnen Ländern zu sein.
2. Grundnormen und Verfahren der Messtechnik auf dem Gebiet der Lichttechnik zu entwickeln.
3. Richtlinien für die Anwendung von Prinzipien und Vorgängen in der Entwicklung internationaler und nationaler Normen auf dem Gebiet der Lichttechnik zu erstellen.
4. Normen, Berichte und andere Publikationen zu erstellen und zu veröffentlichen, die alle Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik betreffen.
5. Liaison und technische Zusammenarbeit mit anderen internationalen Organisationen zu unterhalten, die mit Fragen der Wissenschaft, Technik, Normung und Kunst auf dem Gebiet der Lichttechnik zu tun haben.

Die Arbeit der CIE wird durch Technische Komitees geleistet, die in sieben Divisionen organisiert sind. Diese Arbeit betrifft Gebiete mit grundlegendem Inhalt bis zu allen Arten der Lichtanwendung. Die Normen und Technischen Berichte, die von diesen international zusammengesetzten Divisionen ausgearbeitet werden, sind auf der ganzen Welt anerkannt.

Alle vier Jahre findet eine Session statt, in der die Arbeiten der Divisionen berichtet und überprüft werden, sowie neue Pläne für die Zukunft ausgearbeitet werden. Die CIE wird als höchste Autorität für alle Aspekte des Lichtes und der Beleuchtung angesehen. Auf diese Weise unterhält sie eine bedeutende Stellung unter den internationalen Organisationen.

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MEASURES FOR REDUCING THE ADVERSE EFFECTS OF ARTIFICIAL LIGHT AT NIGHT: INTER-DISCIPLINARY DEVELOPMENT AND PROGRESS

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Abstract

The use of artificial light at night in the outdoor environment may introduce negative and unwanted side-effects such as light pollution and unwanted impacts on humans, ecosystems and biodiversity. Therefore, appropriate measures for reducing the adverse effects of artificial light at night are important to establish a sustainable use of outdoor lighting. This paper presents an updated overview and a state-of-the-art of available and effective measures for reducing artificial light at night, which range from strategical and high-level recommendations to more practical and applicable lighting design recommendations and principles. Another aim is to identify prioritized future research questions and areas that will enhance progress within the area. We present the current recommendations into three groups: (I) recommendations for legislation at the national or international levels, (II) recommendations for technical and practical adaptations of the lighting design and (III) recommendations for sensitive species, taxa, areas or ecosystems.

Keywords: Artificial Light at Night, Light Pollution, Ecological Light Pollution, Recommendations

1 Introduction

The use of artificial light at night (ALAN) in the outdoor environment may introduce negative and unwanted side-effects such as light pollution, which can be defined as “sum total of all adverse effects of artificial light” (CIE, 2020). During recent decades, the adverse effects of ALAN have attracted more and more attention in various research areas, for example, earth and planetary science, physics and astronomy, engineering, environmental science, agricultural and biological sciences and medicine, to mention a few. The research field has expanded from viewing light pollution mainly as an obstacle for astronomical observations (Riegel, 1973) to studies analysing impacts on human health and the natural environment. ALAN can result in unwanted impacts on humans, ecosystems and biodiversity (Bara et al., 2020). For example, trespassing lights may cause discomfort glare (Sim et al., 2017) which may have negative impacts on traffic safety. Other examples include the unwanted attraction of species that exhibits positive phototaxis which may require a higher consideration when planning measures for dealing with the impact of light pollution and priority in management plans for protected habitats (Jägerbrand and Bouroussis, 2021). The impact of light pollution can also result in lower fitness of nocturnal species that require dark areas for their well-being (Sanders et al., 2021).

Several studies have shown that light pollution is increasing globally and regionally in specific regions (e.g., Kyba et al., 2017). Many countries have implemented guidelines or legislation to mitigate the negative impact of light pollution, for example, France (Martinsons, 2019), Australia (Commonwealth of Australia, 2020) and Austria (Bierbaum et al., 2019). There are also some voluntary initiatives for restrictions of outdoor use of light and light pollution in specific areas by planning and following regulations for the use of outdoor lightings, such as International Dark Sky Reserves (IDA, n.d.) and a few other recommendations available, such as, e.g., recommendations for the procurement of European road lighting (Donatello et al., 2019) and the Low Impact Lighting (LIL) (Licht und Natur, n.d.). However, such requirements are not always very useful or practical for implementation especially in cases where outdoor lighting is applied for certain human activities and needs, for example, in the urban environment. In such

applications, ALAN is intended to create visibility, guidance and comfort, or reduce the fear of crimes, or for enhancing traffic safety. Under some circumstances, when lighting conditions are serving specific activities (e.g., sports lighting), the guidelines for reducing the ecological impacts may be especially challenging to be applied. It is important to acknowledge the need for inter-disciplinary joint efforts for successful development within the field of measures for reducing adverse impacts of light pollution. It seems crucial that experts from, for example, the field of lighting engineering and ecology (i.e., ecological impacts of ALAN) are collaborating.

From a sustainability perspective it is important to ensure that the outdoor lighting is in line with goals set by the society, such as, for example, sustainability goals and Agenda 2030 (e.g., Jägerbrand, 2015). Sustainable lighting should fulfil the functional needs of the intended users, be cost- and energy-efficient and result in a minimal environmental impact. A reduction of the adverse impacts of ALAN is therefore of high priority for successful and sustainable lighting installations.

This paper presents an updated overview and a state-of-the-art of available and effective measures for reducing ALAN, which range from strategical and high-level recommendations to more practical and applicable lighting design recommendations and principles. Another aim is to identify prioritised future research questions and areas that will enhance progress within the area.

2 Method

We investigated the currently available measures suggested for reducing the adverse impacts of ALAN by reviewing the scientific literature. Another source of information was the recommendations that was discussed and adopted in the report “Dark and Quiet Skies for Science and Society, Report and recommendations” that was produced by a working group of a United Nations workshop with the task of the preparation of a proposal to the Committee on the Peaceful Uses of Outer Space of United Nations Office for Outer Space Affairs. Also, we developed and systematically classified the measures for reducing ALAN and identified future research questions for enhancing the progress within the area. The recommendations proposed in this paper are developed having in mind all the aspects of ALAN and the corresponding possible affected environmental groups, including humans, fauna and flora.

3 Results

Measures for reducing the adverse effects of ALAN can be divided into three major groups: (I) recommendations and legislation at national or international levels, (II) recommendations for technical and practical adaptations of the lighting design and (III) recommendations for sensitive species, taxa, areas or ecosystems. Examples of recommendations for each group are presented in table 1.

Table 1 – Division in groups for measures for reducing the adverse effects of ALAN

Groups	Examples of recommendations
Recommendations for legislation at national or international levels	Classification of ALAN-free zones, limits of upward emitted light over geographical areas, legislation limiting the negative impact of ALAN
Recommendations for technical and practical adaptations of the lighting design	Precise lighting design: spectral power distribution, lighting control and adaptive lighting concepts, light distribution and orientation
Recommendations for sensitive species, taxa, areas or ecosystems	Measures for reducing impacts on sensitive species and habitats, identifying species and groups that are sensitive and suggesting management of sensitive areas to avoid the impact of ALAN

To mitigate the impact of ALAN on humans and the natural environment 13 different recommendations have previously been suggested, see figure 1 (Bara et al., 2020). We have divided the 13 recommendations into two groups based on their character. Recommendations for areas to be illuminated, a geographical framework to mitigate light pollution, definition of ALAN-free areas and ecosystems, ALAN monitoring measurements, urgent research topics and strategic targets were all classified as recommendations and legislation at national or international levels, while the other seven recommendations were classified as recommendations for technical and practical adaptations of the lighting design (in the context of this paper). Recommendations for reduction of adverse effects of ALAN with focus on sensitive species, taxa, areas, or ecosystems is only marginally dealt with in the 13 recommendations and is therefore described more in detail in an individual chapter (3.3) in this paper.

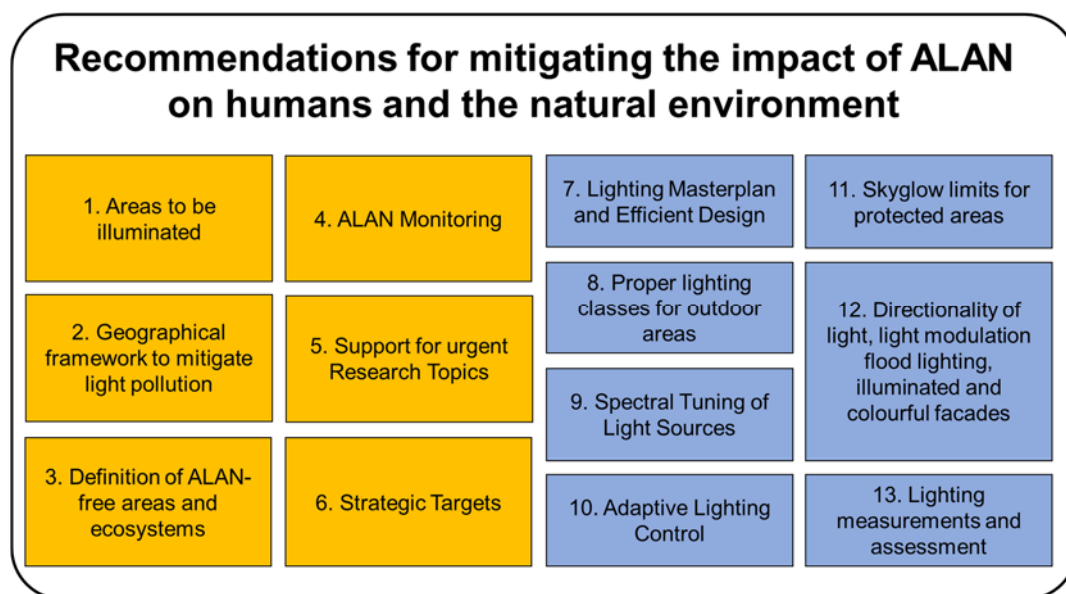


Figure 1 – Recommendations for mitigating the impact of ALAN on humans and the natural environment. Yellow = recommendations for legislation at the national or international levels, blue = recommendations for technical and practical adaptations of the lighting design.

3.1 Recommendations for legislation at the national or international level

At the national and international level, recommendations can be found in a form of general guidance, specific legal limits or legislations, curfews, measures based on specific aims, targets towards working more sustainably or holistically way with outdoor lighting. At the international level recommendations of measures to reduce the adverse impacts of ALAN have recently been published as work aimed for subsequent adoption by the Committee on the Peaceful Uses of Outer Space of the United Nations Office for Outer Space Affairs (Bara et al., 2020). The aim was to produce recommendations that should be useful for regulations for environmentally friendly lighting for countries, regions, municipalities and communities. The strategy behind the recommendations can be summarised by “the right light, at the right place, at the right amount, for the right duration”. With the expression “right light” it is assumed an adequate visual performance (for human functions) while meeting the goals for environmental and health protection. This chapter will present relevant recommendations based on the report by Bara et al. (2020) and then discuss how it is possible to work with sustainable development of outdoor lighting and how sustainability tools can be efficient when aiming for mitigating the adverse effects of ALAN.

The key aspects of the proposed top-level recommendations from figure 1 are described below.

Areas to be illuminated

Areas to be illuminated should be determined, as well as which areas shall be non-lit and protected from ALAN. Governing bodies, such as countries, states, counties should define

criteria for whether areas should be lit. New installations should be justified and unnecessary illumination should be prevented to minimise environmental impacts.

Geographical framework to mitigate light pollution

Within specific areas, maximum admissible light emissions can be determined for various zones and in specific territories. These zones include areas that are urban, suburban, rural and intrinsically dark. Caps on the light emissions will help to stop further deterioration of areas that need protection (see skyglow limits for protected areas in 3.2). Zones of optical observatories, dark sky places and environmental areas should be defined according to the CIE zoning system and the associated limitations should be applied. Existing zoning should be updated to include environmental criteria or new zones can be specifically defined for this purpose. The selection of zones should be the initial action of the master planning procedure. The increase of skyglow should be limited and if possible, be restored to acceptable levels or even to reach the natural levels, especially for certain areas of interest. Limitation of skyglow may probably extend beyond the country or region limits. Therefore, intergovernmental understanding and common actions should be encouraged in terms of long-term strategies for sky glow limitation. In the case of the European Union, the limitation of sky glow elevation can be agreed upon and enforced in terms of EU regulations or relevant actions.

Definition of ALAN-free areas and ecosystems

ALAN-free should be defined to enable the implementation of the strictest limits on the spectrum, shielding and total amount of illumination, even inside cities. Examples of areas that should be ALAN-free are environmentally sensitive areas or ecosystems, intrinsically dark areas, nature reserves and habitats with endangered species in need of protection. The goal of ALAN-free areas is to retain or restore the night sky luminance and the ambient lighting levels to natural levels. Even if this might not be possible everywhere, it is important to protect the environment from further deterioration and to implement adaptation measures to stop direct impacts of ALAN. The zoning system defined by the CIE (2017) for the zones E0 and E1 can initially be adopted for these areas.

ALAN monitoring measurements

It is of high priority to develop frameworks and specify the methods for the monitoring of ALAN and the adverse effects of ALAN at the local and regional levels. This will support the enforcement of the national or international regulations on the mitigation of the adverse effects and ensure that the urban and urban development will not affect the environment above the set limits. Specific public authorities should be charged with the task of regular measurement campaigns, the approval of outdoor lighting installations and other relevant tasks. Verification of lighting installations is probably necessary to avoid over-illumination and to ensure light inflation is not taking place.

Support for urgent research topics

Interdisciplinary research among lighting, medical and environmental research communities on the effects of ALAN on human health, on flora and fauna, on visibility levels and public safety, on thresholds for impacts on humans and natural species and others should be strongly encouraged. Governments and international bodies (e.g., European Union) should include and promote interdisciplinary research in their funding frameworks. The research must use established metrics and lighting research methods to ensure the analyses are based on robust scientific knowledge and that the results can be communicated between disciplines and implemented in the regulatory actions.

Strategic targets

A long-term strategy should be developed in terms of international, national, or regional regulations, to ensure mitigation of unwanted effects of light pollution, to establish standardised measurement systems and accreditation system, for revision of relevant lighting standards and the promotion of lighting education among stakeholders including public authorities and policymakers. Goals for establishment of long-term protection and restoration of negatively impacted areas should be an important strategic target.

Sustainable development

Outdoor lighting should be designed, created and maintained holistically or sustainably way to reduce unwanted and negative consequences. A sustainability framework and sustainability indicators can efficiently be used to assess and monitor the outcome or impact of projects from the three pillars of sustainable development, i.e., the social, economic and environmental dimensions. Environmental indicators are found in four major groups: ecological impact, energy efficiency, light pollution (astronomical light pollution) and trespassing light and life cycle assessment (Jägerbrand 2015).

In general, when mitigating light pollution, a reduction in energy use and ecological impacts will also follow, whereas lighting aimed for higher social sustainability may sometimes cause increased light pollution and energy use (Jägerbrand 2020). It is therefore important to evaluate and assess the lighting installations from a sustainable perspective and to weigh potential negative impacts, such as environmental deterioration for endangered species and increased costs and climate change, against the user's need in the specific location. This can only be achieved if all relevant aspects are fully considered and assessed through indicators, preferably based on metric units, or qualitative units with yes/no answers or percentage of the installations that comply. For example, an (indirect) indicator of ecological impact can be lm/m^2 (lux) or cd/m^2 (luminance) in a given area. Likewise, energy efficiency can be measured and evaluated by the power density indicator, PDI (W/lux/m^2). The framework of sustainability indicators can also be used as a checklist of ways to reduce adverse impacts of ALAN at national or regional scales. A tool based on sustainability indicators or individually chosen indicators can be used as mandatory requirements in the procurement process for lighting installations and should be recommended to be used on a national level for new projects and for upgrading of old installations.

3.2 Recommendations for technical and practical adaptations

The transition of the global lighting industry towards solid-state lighting (LED) and the digitalisation of lighting controls offered new opportunities but on the other hand, negatively contributed to the negative aspects of over-illumination and the adverse effects on humans and the environment. It is therefore essential to revisit the established technical recommendations on outdoor lighting and update them in order to meet the current needs and to address the multidiscipline nature of obtrusive light and its effects on the environment.

In this context, we propose the following top-level technical recommendations as a motivation for local or international legislation and regulation of the industry. These recommendations were originally prepared by the authors and presented in the Bio-Environment working group of the Conference for Dark and Quiet Skies 2020 organised by the United Nations Office for Outer Space Affairs (UNOOSA). The following recommendations are an extended version including the feedback and suggestions from other working-group members as well as aspects of ALAN beyond the environmental impact.

The recommendations for minimising the impact of ALAN are based on the following concept:

- Limit the extent of illuminated areas (spatial distribution)
- Limit the time of illumination (temporal distribution)
- Limit the illuminance levels
- Adjust spectral power distribution
- Reduce, improve and adapt the light in or near protected or sensitive areas
- Control the number of new areas to be illuminated

Lighting masterplan and efficient design

The lighting masterplan should be part of the urban development sustainability studies. The plan. The masterplan should set the requirements for the areas that were selected to be illuminated and their associated lighting needs. It should implement efficient lighting design techniques and the appropriate equipment, optics, lenses, suitable accessories, and other relevant technologies to ensure minimisation of spill, obtrusive and intrusive light. As each area,

region or country has specific characteristics, the masterplan should carefully address the individual character and need of them. The aim is to serve the lighting needs in an optimised way by seen both the whole picture of the area covered but also the technical solutions in the local level.

Proper lighting classes for outdoor areas

The appropriate lighting classes (nominal and adaptive ones) should be selected either in master planning or per case, for all outdoor illuminated areas according to the relevant standard or technical report. Lighting classes set the illumination targets for specific tasks related to human activities. Each class should be carefully selected using the relevant criteria. All aspects should be considered in the selection process. It is proposed to also include environmental criteria linked to potential impact. The associated maintained levels should not be exceeded more than 20% of the minimum requirement of the class. In the case of an adaptive lighting control this can also be reduced close to 0%.

Spectral tuning of light sources

The spectral power distribution of light sources for all outdoor illuminated areas should be carefully selected to ensure minimal influence on sky glow, human health and the environment. Currently, there is not any best spectrum for all applications since different spectra may affect species in different ways. In general, blue light should be minimised and avoided when possible or in specific areas (e.g., using a zoning system like CIE zoning or similar). The selection of the appropriate emitted spectrum should be included in the masterplanning but not limited to it. Recent advances in tunable white technology and other combined sources with various spectra offer the flexibility of using application-specific light sources together with spectrum control over time.

Adaptive lighting control

All outdoor lighting installations should be controlled in terms of luminous flux when the criteria for lowering the lighting class permit it or when there is no presence of users in the area. In addition, control of the spectral distribution of luminaires is encouraged in the case of tunable white luminaires. Current technology offers a variety of solutions for controlling the luminous output of outdoor lighting installations. Motion, presence, traffic and other sensors can also provide an additional level of smartness towards the adaptiveness of the lighting levels according to variable conditions. All new installations and ideally all renovated ones should be designed and implemented together with a proper adaptive lighting control system. This will ensure the minimisation of the excess light when the need for light is reduced or is not applicable for certain periods of the night.

Skyglow limits for protected areas

The elevation of sky brightness during the night should be prevented and restored if possible in certain priority areas, especially for astronomical observatories and dark sky reserves. Sky luminance levels should be kept below certain levels which start from $<260 \mu\text{cd}/\text{m}^2$ for Optical Observatories (DSAG class 1 areas) and up to $<750 \mu\text{cd}/\text{m}^2$ for Dark Sky Community, rural (DSAG class 6b). Even though the application of sky glow limits is not so straightforward as regulations for local lighting, the limits should be defined and adopted as a long-term strategy and target.

Directionality of light, light modulation flood lighting, illuminated and colourful facades

No illumination of architectural structures and signs shall take place during curfew and during other periods, the luminance levels should be as low as possible. Glare from outdoor lighting should be minimised especially the one that effects critical observers like drivers. In addition, intrusive light should be avoided and ideally minimised to zero. Colour and dynamic lighting of facades and signs should be generally avoided especially beyond city centres. Since those elements are illuminated for aesthetical purposes, a balance should be found between cultural heritage, nightscapes and social needs.

Lighting measurements and assessment

The appropriate instrumentation and methods should be used for the measurement, assessment and monitoring of the sky-glow and the sources of obtrusive light. Outdoor lighting

installations should be measured during the construction, operation and maintenance periods and tuned to meet the design requirements while the obtrusive light sources should be identified. The variation of sky glow should be monitored in long term in order to assess the increase or the restoration of the brightness level towards the set target.

3.3 Recommendations for sensitive species, areas or ecosystems

Sensitive areas need to incorporate considerations of occasionally rare, endangered and threatened species. For recommendations in these kinds of areas, it is of crucial importance to understand the species, ecological requirements and the factual impacts of ALAN on the survival and fitness of relevant species. However, various species and taxa have different tolerance for ALAN. Recommendations for sensitive areas and species should therefore always consider both the environment itself but also the relevant species and its tolerance for ALAN. Effective strategies and measures to deal with the ecological impact of ALAN on protected species and habitats have recently been reviewed (Jägerbrand and Bouroussis, 2021) and eight areas of importance have been identified, see table 2.

Table 2 – Areas of importance for sensitive species, areas or ecosystems

Areas of importance
Legislation to effectively deal with the environmental impact of ALAN on species and habitats
Use the best practice guidelines for outdoor lighting within protected or sensitive environments
Establish and recommend levels of the maximum amount of light as optimal criteria for fulfilling different functions for humans
The use of environmental lighting zones and adaptation of lighting design to the appropriate zone
Priorities among species and groups of species
Knowledge of the sensitivity of environments and ecosystems to ALAN
Planning and tools based on landscape ecology and nightscapes
Successful measuring of the ecological impact of ALAN

Legislation to effectively deal with the detrimental impacts of ALAN on the natural environment and protected or sensitive species and habitats is considered of high importance. Examples include environmental protection by an environmental impact assessment and strategic environmental assessments for projects, plans and programs. Conservation of threatened or endangered species must be effectively handled by e.g. establishment of species and habitat lists (red lists) to maintain or restore favourable conditions. Legislation must also be able to protect species from being disturbed by light pollution since disturbances may cause deterioration or destruction of breeding sites or resting places. Feeding sites may also need protection because of potential negative impacts on the ability for feeding and survival. Apart from protecting species and habitats in the planning stage, it is also important to enable protection if disturbances are identified and to force the responsible polluter to take positive action to restore habitats or environmental conditions to improve conservation.

If outdoor lighting is needed within protected or sensitive environments it is recommended to use the best practice guidelines available. If the area was established to preserve protected species that are nocturnal or light-sensitive there is a high risk of negative impacts when using ALAN. It is of special interest to protect, for example, bats, amphibians, reptiles, birds, insects and certain mammals and fish from ALAN (Jägerbrand and Bouroussis, 2021). However, depending on the area in question, other species might be of higher priority. Best practice guidelines often include recommendations for light sources, shielding, limits on upward lighting, lighting control and scheduling/curfews.

The guidelines sometimes include recommendations for maximum illumination levels for different functions for humans. Depending on the type of use, maximum levels of light can be determined if the optimal criteria are known. The main aim is to not use more light than

necessary to achieve the function required for human use and hence, avoid ecological impacts as far as possible.

Environmental lighting zones can be used for dividing geographical areas into zones where various lighting designs and limits for light pollution can be used (CIE, 2017). Zones are differentiated based on the ambient brightness of the environment and are divided into E0 to E4, from intrinsically dark to high district brightness. In the local or regional planning, adaptations of the lighting design are possible based on the environmental lighting zones. This can include, e.g., light sources, limits of upward light, the use of various luminaires and designs.

Priorities among species and groups of species are sometimes necessary due to the higher sensitivity or vulnerability to ALAN or the risk of negative influence at sensitive periods in their life cycles. Hitherto, six potential groups have been identified for prioritisation: nocturnal or crepuscular species, species in vulnerable habitats, species with migrational or seasonal movements, species with positive or negative phototaxis, endangered/threatened species and species with key ecosystem functions (Jägerbrand and Bouroussis, 2021). Species belonging to any of these groups may potentially need higher priority in nature conservation and stronger protection from ALAN.

Adaptations of the lighting design should also consider the overall sensitivity of environments and ecosystems to ALAN. For example, open landscapes with a high number of protected or endangered species would be highly sensitive for ALAN. This is because the open landscape enables far-ranging propagation of ALAN which will expose a large number of species to the light. Another example is aquatic ecosystems that will propagate light and is inhabited by species with a high degree of light sensitivity. It is therefore important to consider the environmental characteristics when planning the lighting design and also to ensure that the ecological aspects, such as sensitive or endangered species, are taken into consideration.

It is recommended to use tools based on landscape ecology and nightscapes when planning the lighting in sensitive areas. Even though this is a relatively new concept in ALAN, ecologists often use landscape tools for nature conservation and environmental impact assessments, etc. Aspects to include are, for example, area brightness, light inflation, over-illuminated areas considered dead ecological zones, barrier effects, migration distances and habitat network and buffer zones.

Measurements of ALAN are important to be able to monitor changes after measures have been implemented or to get information on the levels of ALAN in a specific area. Field measurements in sensitive and protected areas must be carefully designed to be relevant for the species under investigation and the local conditions. The measurements should combine spectral radiance, spectral irradiance, spectral power distribution and the light distribution for the light reaching the selected area or habitat. Measurement location must be carefully selected to be representative, for example, the field of view should follow the species under investigation.

General advice for avoiding severe ecological impacts is to take precautionary actions if the lighting will affect nocturnal and crepuscular species, threatened species, impact on vulnerable times for survival, e.g. night migration, if the species have phototaxis, if there is a risk of ecosystem effects, and if there is a risk of loss of areas with natural darkness with protected species. Moreover, areas and habitats that are more sensitive/vulnerable to light (e.g. aquatic, open landscapes) by increased propagation or due to a higher frequency of sensitive species, may also require precautionary actions or measures. It might be difficult to get information about the presence of species and if they are light-sensitive or not. While the scientific literature can give guidance on the visual systems of species, it is sometimes challenging to establish, for example, a list of nocturnal species that exist within a geographical area. It is therefore important to consult with ecologists and nature conservation officials before installing outdoor lighting in areas that may affect the surrounding environment.

4 Discussion

The illumination of outdoor areas has been driven for years by local needs on safety, aesthetics and the beautification of the nightscape. Cultural and social characteristics have also influenced the illumination methods and most importantly the minimum acceptable lighting levels. It is

known that in many cases that the outdoor illumination, as a combination of lighting design aspects, illumination levels and luminaire types, characterise whole regions or countries. For several years, there was an effort to regulate outdoor lighting by providing lighting design guidelines, illumination levels per working task and technical recommendations for the lighting equipment. CIE played a significant role in the harmonisation of the outdoor lighting guidelines by introducing and maintained several technical reports, mainly by Division 4 and former Division 5. CIE documents were used as the basis for regulations in many countries, especially in the European continent. Similar efforts for the standardisation of outdoor lighting have been undertaken by other organisations. Currently, CIE is actively working on the adverse effects of ALAN via three ongoing specific technical committees, TC4-58 “Obtrusive Light from Colourful and Dynamic Lighting and its Limitation”, TC4-61 “Artificial Lighting and its Impact on the Natural Environment”, TC2-95 “Measurement of Obtrusive Light and Sky Glow and a reportship DR 4-53 “Environmental Aspects of Obtrusive Light from Outdoor Lighting Installations”.

This updated review of the various recommendations that are available for the mitigation of the adverse effects of ALAN from the outdoor lighting shows that there are many possible solutions for reducing light pollution, but that it may require good insight, knowledge and political decisions in both the impacts of the light pollution and an understanding of the technical solutions available to choose the most effective and appropriate measures. Apart from ecological and lighting engineering research expertise, all stakeholder groups must also have a wide experience in working with artificial lighting (i.e., theoretical knowledge, state of the art technology and assessment tools) while the continuous education of stakeholders should keep everyone close to the state of the art knowledge.

Future prioritised research efforts will be beneficial to enhance the progress of reducing the adverse effects of light pollution and be helpful for output from the three ongoing technical committees in CIE. We have identified the following aspects as prioritised:

- Cross-disciplinary investigations are needed to be used as input for development and recommendations. These include impacts on astronomical observations, humans and the natural environment.
- A standardised metrology system for light pollution based on traceable instruments should be developed and used by the different disciplines. Stakeholders should be able to understand the current situation in various areas and ecosystems worldwide and to be able to assess and implement measures against the adverse impacts of ALAN. The standardised methods will help in the establishment of the recommended technical measures ensuring their appropriate application.
- Evidence-based research on the effectiveness of measures to reduce light pollution and the adverse impacts on various species/areas is urgently needed to aid in making improved priority among measures.
- Identification of thresholds and limits for species tolerance (for survival) to ALAN is important for future recommendations for outdoor lighting.
- There is an urgent need for the development of holistic approaches to lighting design guidelines, tools and legislation that can address many goals at once, such as energy use, sustainable development, circular economy and obtrusive and adverse effects of ALAN.
- Investigations are needed on the implementation of adaptive lighting and use of curfews. It is important to estimate how efficient various schemes of adaptive lighting are in reducing light pollution and ecological impacts.

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IS IT POSSIBLE TO ACHIEVE QUALITY LIGHTING WITHOUT CONSIDERING THE PHOTOMETRY OF THE PAVEMENTS?

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Abstract

In this study, the photometry of a wide range of classic and innovative pavements used in urban and interurban areas were characterised both when new and after 30 months of natural aging. An extreme diversity of behaviour with respect to light reflection was revealed both over time and between pavements. The simulations of relamping cases show that the use of typical CIE *r*-tables almost systematically leads to non-compliance with the EN 13201 standard, particularly in terms of uniformity. Taking the photometry of the pavement at its stabilized state into account, simultaneously allows for compliance with lighting safety issues and for significant energy savings. As measurements of pavement photometry are rarely carried out, an alternative is to build up a database of urban pavements, which is one of the objectives of the *Pavements and Lighting* working group.

Keywords: Pavement photometry, Gonioreflectometer, Aging effect, Database, Road lighting design, Relamping

1 Introduction

The lighting installations are designed on the principle of "projected light flux" on a standard road surface. The important for the user is not only the projected luminous flux, but the light reflected by the pavement or the obstacle and thus the luminance. The perception is done by contrast of luminance and this one depends on the properties of the pavement. Road lighting installations are generally designed by calculating the performance in terms of luminance distribution as defined in (CIE 140, 2019) and the EN 13201 European standard (EN 13201-3, 2015). Since the photometric characteristics of the pavements are generally not measured, a standard *r*-table as defined in (CIE 144, 2001) is often used for lighting design. The "standard" *r*-tables are more than 50 years old and several studies have shown that they are no longer representative of actual pavements (Dumont, 2007, Jackett, 2009, Gidlund, 2019, Muzet, 2019a).

Over the past thirty years, several technical, technological, regulatory and societal changes have gradually led to a questioning of the way in which lighting installations are designed and calculated:

- Diversity of road surfaces: we have gone from a few standard road surfaces to an increasingly varied range of surfaces, meeting the requirements of safety, comfort, aesthetics, space structuring and environment. Streets used to be designed and built with the same pavements as roads, this is no longer the case today. Road surfaces, especially urban surfaces, now have such a wide range of surface characteristics (colour, texture, shape) that their photometric properties have been expanded and diversified. The photometric properties of many of them were never measured.
- Technological evolution of lighting systems: the new technologies in lighting installation expand the range of materials and bring more flexibility in their operation,
- Regulatory changes: the NF EN 13201 standard for public lighting allows the project manager to define "photometric levels" and to optimize the project by activating three levels: the equipment, the coating and the organization of the ground plan,

- Societal evolution of street lighting issues: in addition to its primary function of improving safety, in recent years customers have become increasingly aware of the need to reduce energy waste and, above all, to reduce the impact on the environment in order to improve the comfort and lifestyle of citizens.

Despite all these evolutions, it was recently shown in the SURFACE European project that the standard r -tables R3 and C2 are the most used all over the world (Muzet, 2019b), despite the fact that their use can generate important errors (more than 30%) for the average luminance (Chain, 2007, Gidlund, 2019, Muzet, 2019a).

The *Pavement and Lighting* working group (P&L group or in French *Revêtement et Lumière*) is composed of project managers and public authorities*, professional associations and unions of lighting designers** and road builders~, public and private research organisations[‡] and expert consultants. After organizing and monitoring demonstrators and operations on real sites to show the relevance of the challenges and concepts of optimal lighting (Abdo, 2010, Christory, 2014), our goal consists in elaborating a library of actual and innovative urban pavements available on the market to:

- facilitate the choice of decision makers,
- develop tools and methods for managers, lighting designers and road builders to optimize lighting both in interurban and urban areas.

Nowadays the important renewing of lighting installation with a lot of LED relamping creates major new opportunities for road and public space operators. Can these new installations comply with the EN 13201 standard without taking into account the actual road photometry?

A complete characterization of the photometry of our large pavement sample panel was conducted at the initial state and after an outdoor aging of 30 months. It was thus possible to conduct lighting simulations with two considered practical cases of relamping. The quality of the lighting obtained is analyzed by comparison with the criteria defined in (EN 13201-2, 2015).

The paper is organized as follows. In the first methodology part, we recall the basics of road lighting and describe our selection of pavements, our aging and measurement protocol and the lighting calculation methodology. In the second part, the results of the study regarding road surface photometry are given and discussed comparing stabilized and initial photometry. The third part presents the results of the lighting calculations conducted after the stabilisation of the pavement photometry and the impact at the initial stage.

2 Methodology

2.1 Road lighting basics

The surface of a pavement is classified according to its reflection properties (CIE 144, 2001). The most characteristic parameter is the luminance coefficient q , given as:

$$q(\beta, \gamma) = L(\beta, \gamma) / (E_h) \quad (1)$$

It is the ratio between the observed luminance L in cd.m^{-2} which the observer sees, and the illuminance E_h in lux which is incident on the surface (Figure 1).

The standardised viewing height is 1.5 m and the angle of observation α is constant at 1° , corresponding to an observation distance of 86 m. The lighting standards use the area of the road between 60 m and 160 m ahead of the driver, because it is considered an important area for the detection of obstacles. It was also defined for interurban driving where the speed is about 80 to 90 km/h. Since the 1980s, for practical reasons the luminance coefficient was replaced by the reduced luminance coefficient r in $\text{cd.m}^2.\text{lux}^{-1}$, which is derived from q :

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$$r(\beta, \gamma) = 10^4 \times q(\beta, \gamma) \times \cos^3 \gamma \quad (2)$$

A reduced coefficient table called *r*-table was defined, where the luminance coefficient *r* is given for a combination of fixed lighting angles β and $\tan \varepsilon$. The average luminance coefficient Q_0 , represents the degree of lightness of the measured surface. It is computed as the average of the luminance coefficients over the specified solid angle, Ω_0 . The specular factor S_1 represents the degree of specularity (shininess) of the observed surface. It is defined as the ratio between the reduced luminance coefficients of two specific illumination conditions.

$$Q_0 = \frac{1}{\Omega_0} \int q \, d\Omega \quad (3)$$

$$S_1 = \frac{r(\beta=0, \tan \varepsilon=2)}{r(\beta=0, \tan \varepsilon=0)} \quad (4)$$

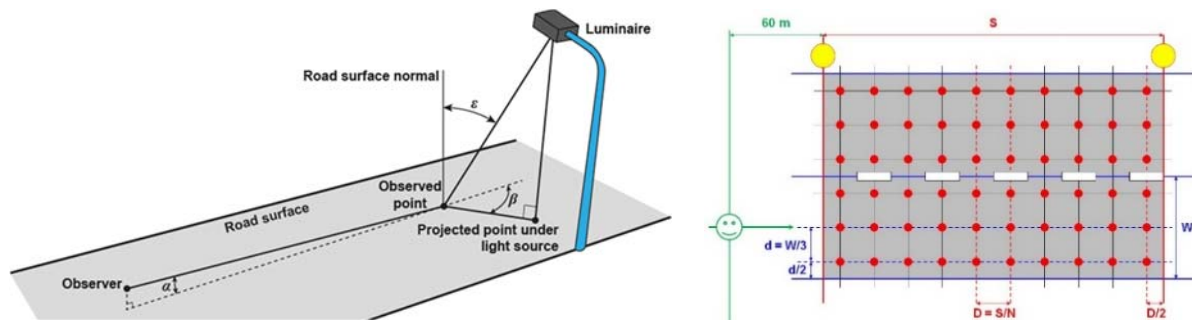


Figure 1 - (left) The photometric characteristics of the road surface depend on the angles of observation α , deviation β and incidence ε . (right) Example of a calculation /measurement grid points (in red) in road lighting design/evaluation, according to the standard (*w* is the traffic lane width, *d* the transversal distance between two lines of points and *D* the longitudinal distance between two columns of points).

The CIE has defined different set of standard *r*-tables that are directly available in all lighting design software (CIE 066, 1984). Since 2001, the CIE (CIE 144, 2001) recommends a scaling of the chosen standard table according to the average luminance coefficient parameters Q_0 . It is obvious that the design of a road lighting system should be based on the knowledge of the actual luminance coefficient for the actual road. Because the actual quantity of *q* is not known, nor is listed as reference values in the EN standard (it provides only the directions in which *q* should be known), designers use in the calculations as *q* reference values the ones given in CIE 144 scientific publication. In France the CIE *r*-tables type R are mostly used.

Guidelines and road lighting standards in Europe give values for illuminance and luminance and their distribution on the road surface according to a grid of points whose number *N* depends on the pole spacing *S* and number of traffic lanes (Figure 1 right). The standard road lighting quality criteria (EN 13201-2, 2015, EN 13201-3, 2015) are derived from the luminance calculated on the grid which are:

- The average luminance L_{ave} , as the arithmetic average of the luminance calculated on each point of the grid;
- Overall uniformity of luminance U_0 , as the ratio of the minimum luminance to the average luminance of the whole grid;
- Lengthwise uniformity of luminance U_l , as the ratio of the minimum luminance to the maximum luminance along the axis of each driving lane;
- Threshold Increment f_{TI} , as the measure of the disability glare;
- Edge Illuminance Ratio R_{EI} , as the ratio of the illuminance on a strip adjacent to the road, to the illuminance on the same strip lying on the adjacent driving lane.

The luminance is calculated from the axis of each lane of the road, embracing the whole width of the grid. For luminance, uniformities and edge illuminance ratio, the lowest value from all lanes is operative. For threshold increment, the highest value is operative.

2.2 The choice and characterisation of the pavements

2.2.2 Methods

The first step was to establish a representative panel of urban and interurban surfacing materials including innovative French technologies. This panel includes 38 different pavements:

- 11 asphaltic concrete (with bituminous or synthetic binder),
- 6 mastic asphalt (with bituminous or synthetic binder),
- 10 poured cement concrete,
- 7 precast cement concrete paving blocks,
- 4 natural stones sett paving.

For each type of pavement, several parameters have been differentiated in order to represent both conventional and innovative pavements used in cities. In particular, the following parameters were variable, depending of materials:

- Formulation: nature and percentage of binder, aggregates granulometry, porosity,
- Poured or precast material,
- Aggregates colour: dark, clear depending of the colour of the used stones,
- Surface treatment: raw pavements, sandblasted, broomed, etc.

Their *r*-tables were measured with the Cerema laboratory gonireflectometer (Figure 2) in order to evaluate their photometric properties (Muzet, 2019). All the pavements were measured at their initial state (called T0) and then installed outside in order to undergo a natural ageing during 30 months (called T30). This ageing implies sun, rain and any other weather condition exposition but not any mechanical influence such as traffic. The ageing applied corresponds to what could be observed on both the central lanes of roads and on urban pavements not used by cars, such as cycle paths, sideways or squares. Nearly all of them except natural stones were measured after 30 months of natural aging.



Figure 2 – Pictures of the Cerema gonireflectometer (left), and of the samples outdoor during natural ageing (right)

For the lighting simulation, seven pavements with light aggregates were selected to test the calculation methodology. Their picture is in the Figure 5 and their characteristics are the following (a short name used afterwards is indicated in brackets):

- Raw very thin asphaltic concrete, clear aggregates size 0/6mm (Raw Asphaltic Concrete)
- Sandblasted very thin asphaltic concrete, clear aggregates size 0/6mm (Sandblasted Asphaltic Concrete),
- Raw asphaltic concrete, synthetic binder, clear aggregates size 0/10 mm + TiO₂ adding's (Raw Synthetic Asphaltic Concrete),
- Bush hammered poured cement concrete, clear aggregates size 0/14 mm (Bush hammered Cement Concrete),

- Draining cement poured concrete, clear aggregates size 4/10 mm (Draining cement concrete),
- Shotblasted soft mastic asphalt, clear aggregates size 0/10 mm (Shotblasted mastic asphalt),
- Shotblasted soft mastic asphalt, synthetic binder clear aggregates size 0/10 mm + TiO₂ adding's (Shotblasted synthetic mastic asphalt).

2.3 The lighting simulations

The second step consisted in conducting lighting simulations, with a representative set of street lighting distributions. The quality of the lighting is analyzed using the criteria defined in the EN 13201 standard (EN 13201-2, 2015, EN 13201-3, 2015). For all our analysis we chose the CIE reference table R3 to make the comparison because it is the most used in France and one of the most used with C2 worldwide (Gidlund, 2019).

Two cases are considered:

1. Case of the classical relamping of a lighting installation where the geometry is imposed and the pavement used for the lighting design remains the standard CIE R3. The luminaire configuration is optimized on this R3 pavement, to minimize the installed power. The quality of the lighting is then computed again, with the same luminaire configuration, taking into account the actual measured r -table when it is new (T0) and after 30 months (T30).
2. Case of the relamping of a lighting installation where the geometry is imposed and the pavement used for the lighting design is the actual stabilized pavement measured at T30. For each pavement, the luminaire configuration is independently optimized to minimize the installed power. The quality of the lighting is then recalculated with the same luminaire configuration, on the same pavement at its initial state (T0). Comparison are conducted with the CIE R3 table.

The lighting simulations are performed on two road profiles:

1. An urban avenue composed of four driving lanes, illuminated by a bilateral lighting installation compliant with a M2 lighting class ($L_{ave} \geq 1.5 \text{ cd/m}^2$, $U_0 \geq 40\%$, $U_l \geq 70\%$, $f_{TI} \leq 10\%$, $R_{EI} \geq 30\%$).
2. A residential street composed of two driving lanes, illuminated by a single-sided lighting installation compliant with a M4 lighting class ($L_{ave} \geq 0.75 \text{ cd/m}^2$, $U_0 \geq 40\%$, $U_l \geq 60\%$, $f_{TI} \leq 15\%$, $R_{EI} \geq 30\%$).

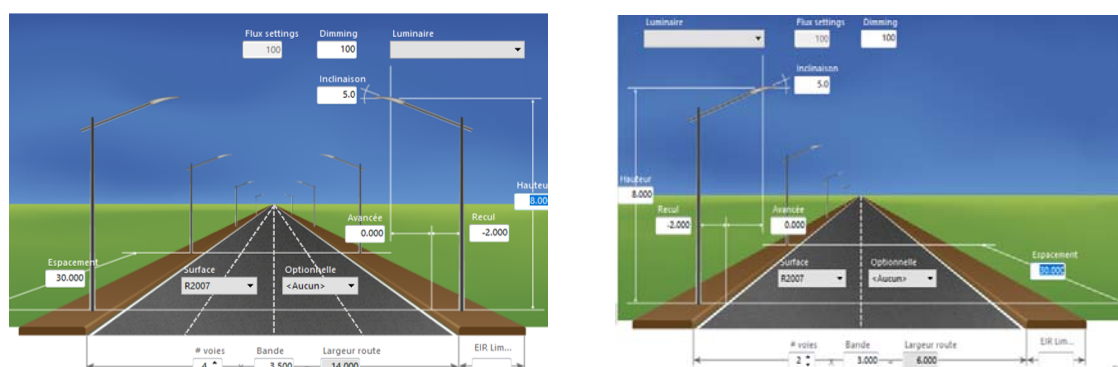


Figure 3 – Representation of the two road profiles: Urban avenue, bilateral opposition (left), Residential street, single-sided (right).

3 Results

3.1 Photometric measurements of urban pavements

The graph of the Figure 4 presents the evolution of Q_0 and S_1 parameters during aging for each sample, the origin of the arrow is the T0 measurement and the arrowhead is the T30 measurement.

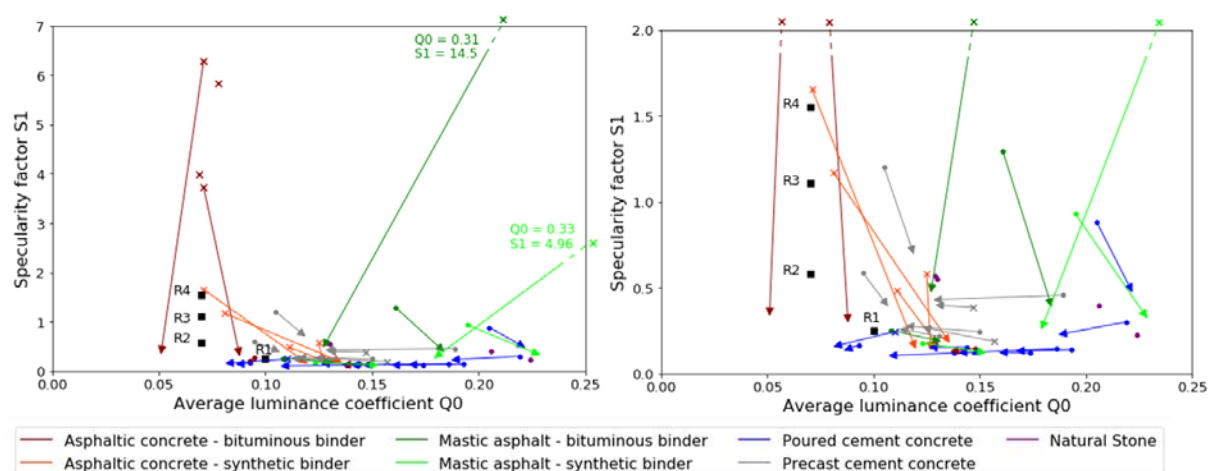


Figure 4 – Representation of the P&L photometric measurements (S_1 and Q_0) for all the pavements. Focus for specularity under 2 ($S_1 < 2.0$) on the right figure.
The initial state T0 is presented with crosses for raw pavements and circles for the others. The T30 measurement corresponds to the arrowheads. The asphaltic concretes are in red and orange, the mastic asphalts in green, the poured cement concrete in blue, the precast cement concrete in grey and the natural stones in violet. The reference CIE r-tables are also presented in black squares.

The characteristics of the seven pavements selected for the lighting simulation are presented in Figure 5 with pictures, Q_0 coefficient, S_1 factor and the corresponding photometric solid at T0 and T30 states.

The results of the photometric measurements of the pavements in their new condition at T0 confirm that there is an enormous diversity of behaviours (Figure 4). After 30 months, the variety fades a little but remains very significant. These results confirm again that the CIE standard tables do not reflect the diversity of all pavements (Dumont, 2007, Gidlund, 2019).

In the Figure 4, almost all the arrows are oriented downwards, which means that there is a drop in specularity with time on the vast majority of pavements. This evolution is really important for the raw asphaltic pavements (concrete and mastic) which were initially very specular but remains more moderate or even negligible for cement concrete samples (both poured and precast). These results are in accordance with previous results (Dumont, 2007, Muzet, 2018, Muzet, 2019a). Binder mainly explains this evolution. Indeed, bitumen is very shiny and specular at its initial state and evolves really fast. On the other hand, cement has a diffuse aspect almost from the beginning. The synthetic binder has an intermediate behaviour with an initial state more specular than cement but much less than bitumen.

After 30 months, 4 samples are CIE R2 type and all the 26 others are classified as CIE R1 type, mainly due to this specularity evolution. Such low values of specularity are not usually measured on conventional circulated road surfaces (Dumont, 2007, Gidlund, 2019) but it was shown in (Jackett, 2009) that non circulated pavements were more diffuse after aging than the ones exposed to traffic.

The evolution with time of the average luminance coefficient Q_0 also differs depending on the pavement surface material. Except for initially very specular surfaces, for the asphaltic concrete and mastic asphalt samples, the luminance coefficient increased between T0 and T30. In accordance with the samples visual evolution (figure 5), a general explanation could be that ageing with meteorological condition has a kind of tarnishing effect on these samples, slightly lightening their surface. On the contrary, the luminance coefficient of cement concrete almost systematically slightly decreased. Since the surface of these samples was quite light from the start, ageing seems to darken them slightly, which is rather confirmed by the visual evolution. As above, this behaviour is not observed when the T0 samples were more specular.

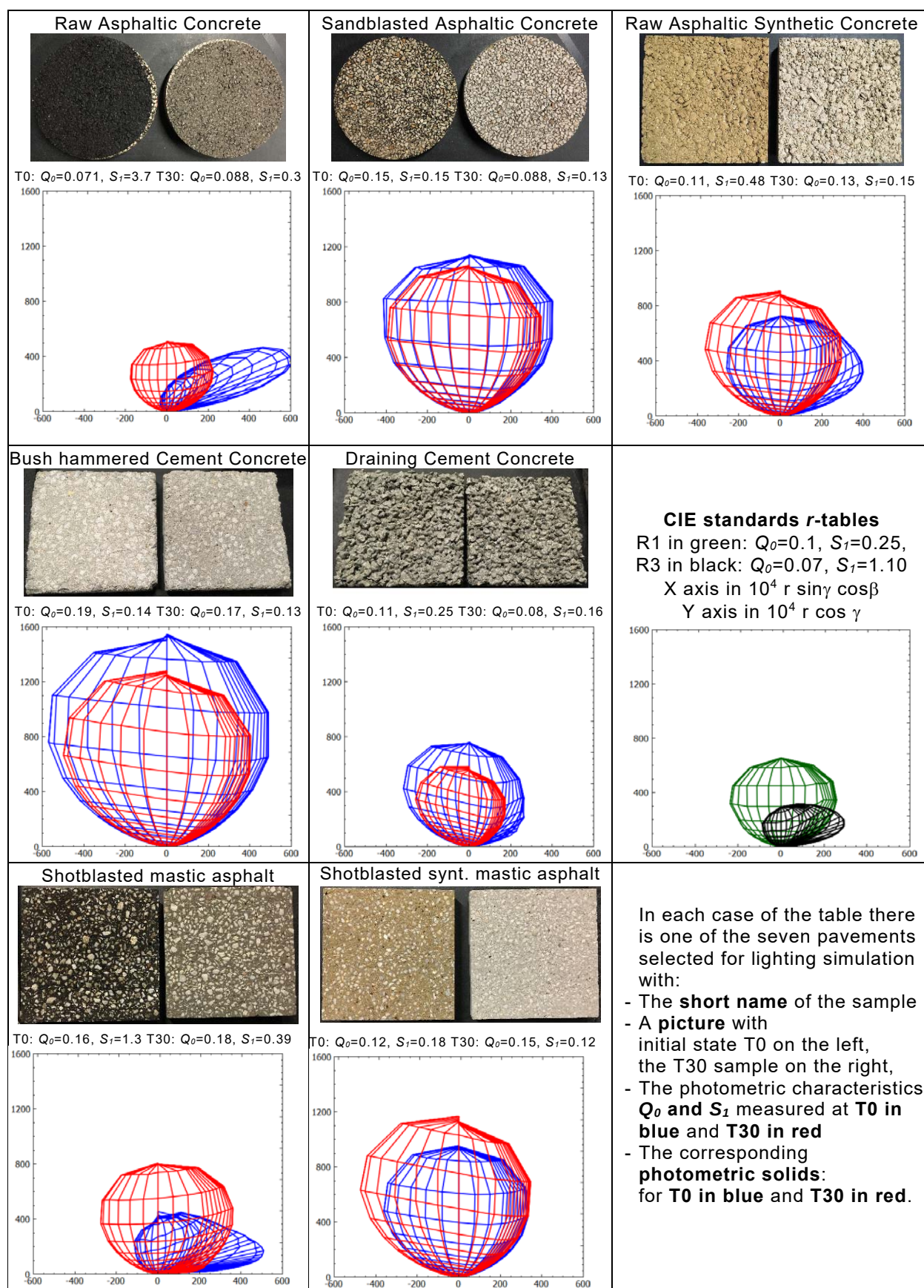


Figure 5 – The seven pavements selected for the lighting simulation - Pavement name, surface aspect (pictures) and photometric characterization (Q_0 , S_1 and solid) evolution from its initial state (T0) and after 30 months of natural outdoor aging (T30).

3.2 The lighting simulations

3.2.1 Case 1 – Relamping with CIE pavement

In case 1 of the lighting simulations, the LED relamping is designed with the standard R3 CIE table. The corresponding lighting criteria obtained with the different pavements at their initial and stabilized state is presented in the table 1 for the bilateral avenue profile and in the table 2 for the residential street profile.

Table 1 – Case 1 Relamping with an optimisation for the *r*-table R3 – Profile 1 Urban avenue. Results on the stabilised pavement (T30) in bold and on the new pavement (T0).

Pavement				CIE class	Luminance						Glare TI		Standard conformity
Name	Age	Q0	S1		Lmoy ≥ 1,50 cd/m²	DELTA Lmoy /standard	Uo ≥ 40 %	DELTA Uo /standard	UI ≥ 70 %	DELTA UI /standard	TI ≤ 10 %	DELTA TI /standard	
CIE R3 table - Reference	-	0.07	1.11	R3	1.50	0%	59	47%	80	14%	10	-1%	OK
Raw Asphaltic Concrete	T30	0.088	0.295	R1	1.71	14%	71	76%	57	-18%	9	-11%	NOK
Raw Asphaltic Concrete	T0	0.071	3.74	R4	1.77	18%	43	7%	57	-19%	9	-13%	NOK
Sandblasted Asphaltic Concrete	T30	0.136	0.128	R1	2.77	85%	63	56%	43	-38%	6	-39%	NOK
Sandblasted Asphaltic Concrete	T0	0.148	0.148	R1	3.06	104%	63	57%	44	-37%	6	-44%	NOK
Raw Synthetic asphaltic Concrete	T30	0.131	0.153	R1	2.62	74%	66	64%	48	-31%	6	-37%	NOK
Raw Synthetic asphaltic Concrete	T0	0.111	0.484	R2	2.45	63%	62	54%	65	-7%	7	-33%	NOK
Bush hammered Cement Concrete	T30	0.167	0.132	R1	3.41	127%	63	58%	44	-37%	5	-49%	NOK
Bush hammered Cement Concrete	T0	0.193	0.14	R1	3.98	166%	63	59%	44	-37%	5	-55%	NOK
Draining cement concrete	T30	0.081	0.157	R1	1.70	13%	68	70%	50	-29%	9	-10%	NOK
Draining cement concrete	T0	0.11	0.245	R1	2.44	63%	62	54%	59	-16%	7	-33%	NOK
Shotblasted mastic asphalt	T30	0.184	0.386	R1	3.15	110%	71	76%	60	-14%	5	-45%	NOK
Shotblasted mastic asphalt	T0	0.161	1.29	R3	2.71	80%	57	42%	75	7%	6	-38%	OK
Shotblasted synthetic mastic asphalt	T30	0.153	0.122	R1	3.14	109%	63	57%	44	-37%	5	-45%	NOK
Shotblasted synthetic mastic asphalt	T0	0.123	0.177	R1	2.59	72%	69	71%	49	-30%	6	-36%	NOK

Table 2 – Case 1 Relamping with an optimisation for the *r*-table R3 – Profile 2 Residential street. Results on stabilised pavement (T30) and on new pavement (T0).

Pavement				CIE class	Luminance						Glare TI		Standard conformity
Name	Age	Q0	S1		Lmoy ≥ 0,75 cd/m²	DELTA Lmoy /standard	Uo ≥ 40 %	DELTA Uo /standard	UI ≥ 60 %	DELTA UI /standard	TI ≤ 10 %	DELTA TI /standard	
Reference: CIE R3 table	-	0.07	1.11	R3	0.75	0%	57	43%	80	84%	10	-1%	OK
Raw Asphaltic Concrete	T30	0.088	0.30	R1	0.85	14%	67	68%	58	-4%	10	-34%	NOK
Raw Asphaltic Concrete	T0	0.071	3.74	R4	0.91	21%	39	-1%	52	-13%	9	-43%	NOK
Sandblasted Asphaltic Concrete	T30	0.136	0.13	R1	1.40	86%	57	42%	43	-28%	7	-55%	NOK
Sandblasted Asphaltic Concrete	T0	0.148	0.15	R1	1.54	105%	57	43%	44	-26%	6	-59%	NOK
Raw Synthetic asphaltic Concrete	T30	0.131	0.15	R1	1.31	75%	60	51%	48	-19%	7	-53%	NOK
Raw Synthetic asphaltic Concrete	T0	0.111	0.48	R2	1.25	66%	59	48%	73	21%	7	-52%	NOK
Bush hammered Cement Concrete	T30	0.167	0.13	R1	1.72	129%	58	44%	44	-26%	6	-62%	NOK
Bush hammered Cement Concrete	T0	0.193	0.14	R1	2.00	167%	59	47%	44	-27%	5	-66%	NOK
Draining cement concrete	T30	0.081	0.16	R1	0.86	15%	60	51%	50	-16%	10	-34%	NOK
Draining cement concrete	T0	0.11	0.25	R1	1.26	68%	60	50%	63	6%	7	-52%	OK
Shotblasted mastic asphalt	T30	0.184	0.39	R1	1.56	108%	67	67%	61	1%	6	-60%	OK
Shotblasted mastic asphalt	T0	0.161	1.29	R3	1.33	78%	54	36%	73	22%	6	-58%	OK
Shotblasted synt. mastic asphalt	T30	0.153	0.12	R1	1.58	111%	58	44%	44	-27%	6	-59%	NOK
Shotblasted synt. mastic asphalt	T0	0.123	0.18	R1	1.31	75%	65	62%	49	-18%	7	-53%	NOK

When the actual photometry of the different type of pavements is integrated into the simulation to calculate the lighting quality criteria, the requirements of the standard are rarely met for the pavements in their initial state (T0). With the measurements carried out in the stabilised condition (T30), there is still a high proportion of non-compliant photometric results. When the actual pavement is not taken into account for the design, the results on the two road profiles show that the most sensitive parameter is the longitudinal uniformities. This poor longitudinal uniformity results in alternating dark and light stripes and can cause safety problems.

The higher values of average luminance on the actual pavements are a consequence of their Q_0 values, which are 14% to 270% higher than the standard Q_0 value associated to R3 (0.07). This shows a potential to reduce the required luminous flux, and therefore the installed power, provided that a suitable light distribution can be used such as to provide compliant uniformities on the actual pavements.

3.2.2 Case 2 – Relamping with actual pavement

In case 2 of the lighting simulations, the LED relamping is designed while taking into account the actual stabilised *r*-table of each measured pavements (T30). The results of lighting optimisation at T30 are presented in the table 3 for the bilateral avenue profile and in the table 4 for the residential street profile.

When taking into account the actual stabilized pavements (T30) to achieve the lighting design, it is possible to find compliant results with all pavements for the two profiles. This allows to optimize the luminous flux required and therefore the installed power. Power savings of 50% to 60% are possible, within the first set of light pavements presently considered.

Table 3 – Case 2 Relamping with an optimisation on T30 actual pavements – Profile 1 Urban avenue with bilateral lighting. Results for the seven selected pavements at their stabilized state T30 (in bold) and at T0.

Pavements					Luminance						Glare		Energy aspect			Standard conformity
Name	Age	Q0	S1	CIE class	Lmoy ≥ 1,50 cd/m²	DELTA Lmoy / standard	Uo ≥ 40 %	DELTA Uo / standard	Ui ≥ 70 %	DELTA UI / standard	Ti ≤ 10 %	DELTA Ti / standard	Lamp power (W)	kwh/km	Power saving / R3 Ref.	
CIE R3 table - Reference	-	0.07	1.1	R3	1.52	1%	59	47%	80	14%	10	-1%	51.2	3.48		OK
Raw Asphaltic Concrete	T30	0.088	0.3	R1	1.52	1%	62	54%	71	2%	8	-20%	46.1	3.14	-10%	OK
Raw Asphaltic Concrete	T0	0.071	3.7	R4	1.35	-10%	41	3%	43	-39%	9	-13%	46.1	3.14	-10%	NOK
Sandblasted Asphaltic Concrete	T30	0.136	0.1	R1	1.52	1%	66	64%	77	10%	5	-54%	28.7	1.95	-44%	OK
Sandblasted Asphaltic Concrete	T0	0.148	0.1	R1	1.67	11%	67	67%	79	14%	4	-57%	28.7	1.95	-44%	OK
Raw Synthetic asphaltic Concrete	T30	0.131	0.2	R1	1.53	2%	75	87%	74	5%	8	-19%	30.9	2.10	-40%	OK
Raw Synthetic asphaltic Concrete	T0	0.111	0.5	R2	1.34	-11%	76	90%	79	12%	9	-10%	30.9	2.10	-40%	NOK
Bush hammered Cement Concrete	T30	0.167	0.1	R1	1.55	3%	72	81%	70	-1%	6	-36%	24.6	1.67	-52%	OK
Bush hammered Cement Concrete	T0	0.193	0.1	R1	1.81	21%	72	81%	69	-1%	6	-44%	24.6	1.67	-52%	NOK
Draining cement concrete	T30	0.081	0.2	R1	1.56	4%	69	73%	70	0%	8	-21%	50.9	3.46	-1%	OK
Draining cement concrete	T0	0.11	0.2	R1	2.13	42%	72	80%	69	-1%	6	-38%	50.9	3.46	-1%	NOK
Shotblasted mastic asphalt	T30	0.184	0.4	R1	1.54	3%	48	20%	74	5%	9	-13%	23.5	1.60	-54%	OK
Shotblasted mastic asphalt	T0	0.161	1.3	R3	1.41	-6%	32	-19%	65	-7%	9	-6%	23.5	1.60	-54%	NOK
Shotblasted Synt. mastic asphalt	T30	0.153	0.1	R1	1.53	2%	73	82%	71	1%	7	-32%	26.1	1.78	-49%	OK
Shotblasted Synt. mastic asphalt	T0	0.123	0.2	R1	1.24	-18%	74	85%	73	4%	8	-19%	26.1	1.78	-49%	NOK

Table 4 – Case 2 Relamping with an optimisation on T30 actual pavements – Profile 2 Residential street. Results for the seven selected pavements at their stabilized state T30 (in bold) and at T0.

Pavements					Luminance						Glare		Energy aspects			Standard Conformity
Name	Age	Q0	S1	CIE class	Lmoy ≥ 0.75cd/m²	Delta Lmoy / standard	Uo ≥ 40 %	Delta Uo / standard	Ui ≥ 60 %	Delta UI / standard	Ti ≤ 10 %	Delta Ti / standard	Lamp power (W)	kwh/km	Power saving / R3 Ref.	
Reference: CIE R3 table	-	0.07	1.11		0.75	0%	57	44%	84	39%	10	-31%	28.6	0.97		OK
Raw Asphaltic Concrete	T30	0.088	0.30	R1	0.75	0%	52	29%	67	12%	13	-15%	25.0	0.85	-13%	OK
	T0	0.071	3.74	R4	0.84	12%	25	-38%	48	-21%	9	-40%	25.0	0.85	-13%	NOK
Sandblasted Asphaltic Concrete	T30	0.136	0.13	R1	0.77	2%	47	18%	61	2%	10	-34%	13.6	0.46	-53%	OK
	T0	0.148	0.15	R1	0.85	13%	46	16%	62	3%	7	-54%	13.6	0.46	-53%	OK
Raw Synthetic asphaltic Concrete	T30	0.131	0.15	R1	0.75	0%	51	26%	67	12%	8	-50%	14.0	0.48	-51%	OK
	T0	0.111	0.48	R2	0.75	0%	41	2%	84	40%	8	-48%	14.0	0.48	-51%	OK
Bush hammered Cement Concrete	T30	0.167	0.13	R1	0.75	0%	48	20%	62	3%	6	-60%	10.7	0.37	-62%	OK
	T0	0.193	0.14	R1	0.87	17%	47	17%	62	3%	5	-64%	10.7	0.37	-62%	OK
Draining cement concrete	T30	0.081	0.16	R1	0.76	1%	49	22%	66	11%	12	-21%	21.2	0.72	-26%	OK
	T0	0.11	0.25	R1	1.14	52%	42	5%	72	20%	9	-40%	21.2	0.72	-26%	OK
Shotblasted mastic asphalt	T30	0.184	0.39	R1	0.75	0%	46	16%	75	25%	6	-58%	11.1	0.38	-61%	OK
	T0	0.161	1.29	R3	0.69	-7%	34	-14%	77	28%	7	-56%	11.0	0.37	-62%	NOK
Shotblasted synthetic mastic asphalt	T30	0.153	0.12	R1	0.79	5%	50	24%	62	3%	7	-56%	12.3	0.42	-57%	OK
	T0	0.123	0.18	R1	0.66	-12%	47	17%	68	14%	8	-49%	12.3	0.42	-57%	NOK

If we simulate the lighting quality for the corresponding new pavements at T0, the standard is not always fulfilled but the discrepancies with the limits are usually moderate. This is illustrated in the above tables, mostly due to insufficient values of overall and/or lengthwise uniformities of luminance. This seems typical of new pavements with a high degree of specularly, that decreases with ageing. For pavements with initial surface treatments, the standard is fulfilled at T30 and T0.

4 Conclusions & perspectives

Our study has confirmed that the enormous range of photometric characteristics of current urban pavements cannot be described by the CIE standard tables (Dumont, 2007, Gidlund, 2019, Muzet, 2019a). Our panel of pavements includes both classic pavements and innovative pavements, even specific to urban environments. Some of these pavements were never characterized before as they are not used in interurban conditions where road photometry is mainly applied for now. The evolution over time differs greatly depending on the type of

pavement and as already recommended in the (CIE 066, 1984) document, it is necessary to carry out lighting with stabilized characteristics (after 1 or 2 years of implementation).

We have shown that during the current relamping operations (case 1), the use of a typical CIE table leads to a non-compliance of the standard with risks of:

- strong over-lighting if the pavements in place are clear,
- bad to very bad uniformity which can lead to road safety problems.

With relamping based on an optimization on energetic aspect considering a stabilized pavement (case 2), all the specifications of the standard are met and thus the lighting installation complies with the safety of users. In addition, substantial savings can be made with clear coatings (up to 50% and 60%). Finally, even if the pavement is new and the standard not fulfilled initially, the quality of the lighting is better than if the characteristics considered corresponds to a CIE standard pavement.

For our selection of pavements, the choice was made to consider rather light-coloured pavements that can allow energy savings. The results presented on this sample of pavements chosen to develop the calculation method should not be considered as qualifying the families of concretes, asphalts and others. Each of these families has a range of responses covering a wide range of performance in the optimization. Moreover, our traffic-free aging is relevant for urban pavements with little or no traffic but cannot be generalized to roads with high traffic.

The next steps are to make the calculations for our complete database of 38 pavements and also to make simulation for brand new installations, with lighting optimisation on lamp spacing considering both pavement and lighting photometry.

When a lighting installation is renewed, it is fundamental to take into account the pavement photometry. With the usual practice of considering a standard r -table, the EN 13201 criteria are generally not fulfilled, especially in terms of luminance uniformities. The diversity of photometry in today's pavements is huge and taking them into consideration can increase the quality of lighting and provide significant energy savings. Because of the possibility of having several optics in the luminaires, it will soon be possible to design adaptive luminaires that could adapt their photometry to the evolution of the existing coating. Knowing that the photometry of some pavements evolves very strongly in the first year (CIE 066, 1984, Dumont, 2007, Muzet, 2019), another solution is to apply an initial surface treatment to avoid the initial specularity and the first year uniformity problems.

With the constitution of a measurement database of actual pavements, this project will contribute to the CIE TC 4-50 (Road surface characterization for lighting applications) and work on EN 13201 standard.

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CHARACTERISATION OF LUMINESCENT ROAD MARKINGS

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Abstract

Photoluminescent paints for road marking have been evaluated through laboratory measurements and visibility computations. The luminance decay in the dark was measured after constant excitation during at least six hours. To study the effect of night-time lighting conditions, luminance was also measured under a constant low illumination simulating moon and light pollution, and a periodic lighting simulating automotive traffic. Measurements were also carried out on luminescent road markings applied in a full scale mock up. Then, possible uses and limits of photoluminescent road markings were investigated through visibility computations based on the COST 331 model. Findings suggest that luminescent road markings could strengthen the visual guidance of drivers on the road with traffic by increasing the visibility distance beyond the range of the headlamps during the first few hours of the night, but it depends on the night-time illumination level.

Keywords: luminescent road markings, glow-in-the-dark, visibility

1 Introduction

Road markings help motorists to control and anticipate their trajectory. This is especially true at night, when other visual cues are less visible. In unlit areas, retro-reflective markings are visible when illuminated by vehicle headlights. Nowadays, innovative products may increase the visibility distance of visual cues, improving the guidance in unsafe situations (e.g. Shahar et al., 2018). In particular, luminescent road markings are being developed in order to allow the markings to be visible beyond the range of the headlamps. Luminescent markings emit light after absorbing photons from sunlight or headlamps with a delay from a few nanoseconds to several hours. The intensity of this emission depends on the quantity and of the spectral power distribution (SPD) of the light previously absorbed.

To be applied on the road, luminescent markings must ensure performance at least equivalent to traditional markings, especially in terms of colour and brightness during the day, and retro-reflection at night (CEN, 2018). In addition, understanding the temporal evolution of its colour and luminance is required to characterize these products. Standards already exist for safety luminescent products, used for emergency signage in buildings, based on the luminance in the dark during the first hour of emission (ISO 17398, 2004). In the road context, we are interested in longer emission times, in various night-time illumination conditions, with road traffic, and in low viewing angles, corresponding to the vision of a motorist ($<2.5^\circ$) or a cyclist ($\sim 10^\circ$, see Chain & Marchaud, 2008).

Since 2014, corresponding to the first road tests of such “glow-in-the-dark” road markings in the Netherlands (BBC, 2014), a few publications have explored the possibility of using strontium aluminate crystals for road marking (Giuliani & Auteliano, 2014; Bullough et al., 2014; Bacero et al., 2015; Pratico et al., 2016, 2018) or other road applications (e.g. Weise et al., 2019; Saleem & Hosoda, 2021). Giuliani & Auteliano (2014) compared different types of luminescent products and demonstrated that the luminescence of strontium aluminate lasts much longer than with conventional powders. In terms of duration, the afterglow of the best tested product did not last in the dark beyond 2 hours, and simulated traffic of halogen vehicle headlamps did not keep the emission going overnight. The authors based their analyses on a theoretical visibility limit of 0.3 mcd/m^2 . Botterman & Smet (2015) also investigated the relevance of such powder for luminescent road markings depending on the temperature and the illumination. Based on calculations, they estimated that the recharge of the product by the traffic only slows the fall in luminescence which decreases through the night. To interpret luminance in terms of

visibility, the authors discussed the threshold of 0.3 mcd/m^2 , with reference to the absolute threshold of perception, which is relevant in the dark, but not on the road. Bullough et al. (2014) used a threshold of 0.01 cd/m^2 . Their luminescent samples measured in the laboratory provide a luminance in the dark above this threshold from 10 minutes to 4 hours after an excitation under a luminaire providing $50\,000 \text{ lx}$ with a metal halid lamp.

In previous work, luminescent markings performances was mostly assessed by comparing the luminance in the dark to a luminance threshold. But since the main function of road markings is the visual guidance, the most relevant indicator is the visibility distance of the markings at night (CIE, 1992). The COST 331 report (1999) of the European Commission proposes a method, based on Adrian's Visibility Level model (Adrian, 1989), for calculating the visibility distance from the luminance of a road marking, its width, the geometry of the road and the driver's age.

In this context, the present paper proposes a method to characterize the performance of luminescent road markings based on laboratory measurements and visibility computations with the COST 331 model. The potential use of this type of product is discussed.

2 Material and method

2.1 Laboratory measurements

2.1.1 Samples

The measurements were carried out on various LuminoKrom® samples, produced during the I-Street research project. Paint was deposited on aluminium plates and asphalt plates made in the laboratory, at various stages of the development of the product. Application was manual with a roller or with a road marking machine. Table 1 provides the characteristics of the samples used in this study (see illustrations Fig. 1). No retro-reflective samples are considered in this paper (all were class R0 according to the EN 1436 standard). Chromatic coordinates were measured with a spectro-photometer CM-2500C after 5 minutes of excitation under D65 illuminant enhanced with UV. Figure 1 presents a white luminescent paint (center) sample, which meets the chromaticity requirements of the EN 1436 standard (CEN, 2018), and a green one (right).

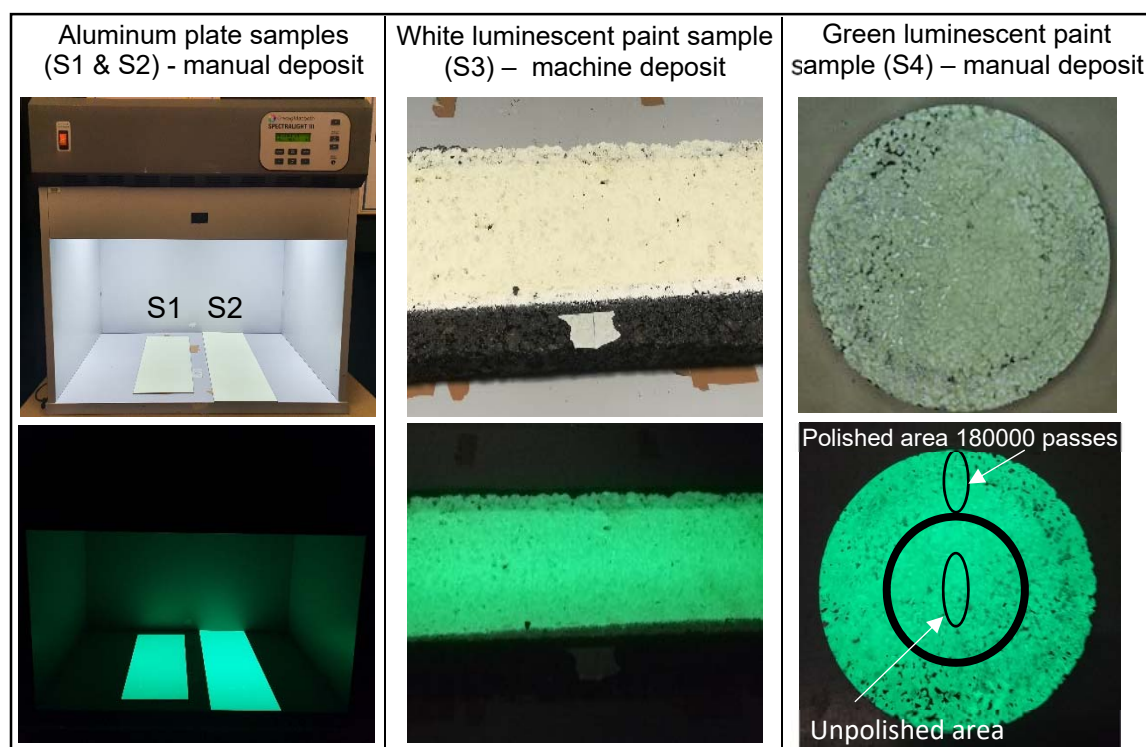


Figure 1 – Examples of samples. Left: Aluminium plate samples in the light booth (S1 & S2); Center: White luminescent paint sample S3; Right: Core sample S4 of green luminescent paint artificially worn with a Wehner & Schulze machine. The ellipses corresponds to the luminance measurement zones.

Table 1 – Laboratory sample characteristics

Name	Support	Application	Chromatic coordinates [x,y]
S1	aluminium	manual (roller)	[0.332,0.374]
S2	aluminium	manual (roller)	[0.330,0.374]
S3	asphalt	machine	[0.337,0.363]
S4	asphalt	manual (roller)	[0.357,0.401]

2.1.2 Colour measurement

The chromatic coordinates of a luminescent paint sample deposited on an aluminium plate (S1) was measured at a 90° observation angle with a spectroradiometer CS1000 during 30 minutes of excitation with a D65 illuminant and then during ten hours of emission in the dark.

2.1.3 Luminance measurement in the dark

The simplest characterisation of a luminescent paint is to measure the luminance decay in the dark after constant excitation. The paint was excited for 30 minutes in a light booth (Spectralight III X-Rite) at 1.5 klx horizontal illuminance with a D65 illuminant enhanced with ultraviolet (see Figure 1, left). Then, the sample was placed in a dark room and the luminance was measured every 10 minutes with a spectroradiometer PR770 during six to ten hours. The measurement was carried out with an observation angle of 2.29° corresponding to a driver according to the EN1436 standard (CEN, 2018). The luminance measured in the dark as a function of time is called the decay curve.

To investigate the durability of the product's afterglow, the measurements were also conducted after artificial ageing. To that purpose, a core sample of a Very Thin Layer Asphalt Concrete plate (S4) was polished with 180000 roller passes with a Wehner & Schulze machine. Then, the decay curves of the polished area and of the central unpolished area were measured (see Figure 1).

The emission in complete darkness is a theoretical reference situation, which does not correspond to the real situation on the road. To study the effect of night-time lighting conditions, two scenarios have been studied in the laboratory: constant low illumination, such as moon or light pollution, and periodic lighting, simulating automotive traffic.

2.1.4 Luminance measurement under constant illumination

Night-time illumination was simulated with a constant horizontal illuminance on the sample of 0.01, 0.05, 0.1 or 0.5 lx, using a RGB LED Matrix (behind a diffuser) controlled by Arduino. Although the SPD was questionable, it allowed providing a controlled low diffuse illuminance on the samples. Using the same excitation protocol described in Section 2.1.3, the decay luminance of a luminescent sample was measured every hour during seven hours (averaged over five measurements) with a luminancemeter PR880 at a 2.29° observation angle. The luminance of fully discharged samples was also measured under each illuminance level.

2.1.5 Luminance measurement under cyclic illumination

The same RGB LED Matrix was used to simulate a periodic illumination due to road traffic. The horizontal illuminance variation on road markings due to real LED low-beam headlights was simulated. Based on the horizontal illuminance profile, it was possible to simulate different vehicle speeds and different traffic densities (in veh/h). This periodic lighting was applied during six hours in the dark, the sample being previously excited as in Section 2.1.3. The luminance of luminescence was measured every hour with a luminancemeter PR880 at a 2.29° observation angle (averaged over 5 to 10 measurements) when the LED was switched off.

2.2 Measurements on real road markings

To investigate more realistic conditions, a white and a green luminescent road markings were applied in an urban innovation demonstrator located in a climatic chamber, called Sense-City (<https://sense-city.ifsttar.fr>). The luminance of the two road markings at a 2.29° observation angle was measured with a spectroradiometer PR740 every five minutes during three simulated sunsets representative of those occurring during a year in Lyon, France, and then every ten minutes during six hours in the dark. The sunset was simulated by decreasing every 15 minutes a controlled artificial sun (32 metal halid lamps, 22600lm, 5600K) during the two hours before civil twilight. The three sunsets were determined conducting a hierarchical ascendant clustering analysis (euclidean distance) of the horizontal illuminance measured during the two hours before the civil twilight in 2018, extracted from the IDMP Database of ENTPE (<http://idmp.entpe.fr/mesfr.htm>). The main characteristics of the mean sunsets are as follows:

- C1: from 2500 lx at -120 min to 11 lx at -15 min, 32.6% of the year,
- C2: from 7000 lx at -120min to 17 lx at -15 min, 42.2% of the year,
- C3: from 11000 lx at -120 min to 30 lx at -15 min, 23.8% of the year.

The ambient temperature was kept constant at 12°C ($\text{SD}=0.05$), and the road surface temperature was around 13°C (13.5°C when the sun was switched on). The mean relative humidity was 77.1% ($\text{SD}=1.7\%$).

2.3 Visibility computations

From the laboratory measurements of samples S2 and S3 and the calculation method proposed in the COST 331 report (1999), the visibility distance of the luminescent marking beyond the headlamp beam was estimated, and compared to the visibility distance of a traditional retroreflective marking in low beam headlights. Computations were based on the assumption that with equivalent R_L , the luminescent markings only provide significant added value if it is visible beyond the beam of the headlights. The visibility distance corresponds to a Visibility Level threshold of 10 (COST 331, 1999).

A continuous central line of 7.5 cm width on a straight and flat road with lane width of 3.5 m and dark asphalt ($Q_d=60 \text{ mcd/m}^2/\text{lx}$, $R_L=10 \text{ mcd/m}^2/\text{lx}$) was considered. A traditional retroreflective marking ($Q_3 Q_d=130 \text{ mcd/m}^2/\text{lx}$, $R_4 R_L=200 \text{ mcd/m}^2/\text{lx}$) illuminated by the theoretical low beam headlights of the COST 331 tool (intensity factor 1, i.e. 10000 cd) was taken as a reference for comparison.

3 Results

3.1 Colour variations

The colour of luminescent markings changes over time. During the day, it depends on the reflection and fluorescence properties of the product, and on the SPD of daylight. At night, the luminescence emission spectrum shifts the chromaticity towards green. Figure 2 shows the “colorimetric trajectory” during the excitation and the emission in the dark of a sample of luminescent paint (S1). The significant change in colour between day and night raises questions about the appropriate measurement method to characterize this class of products.

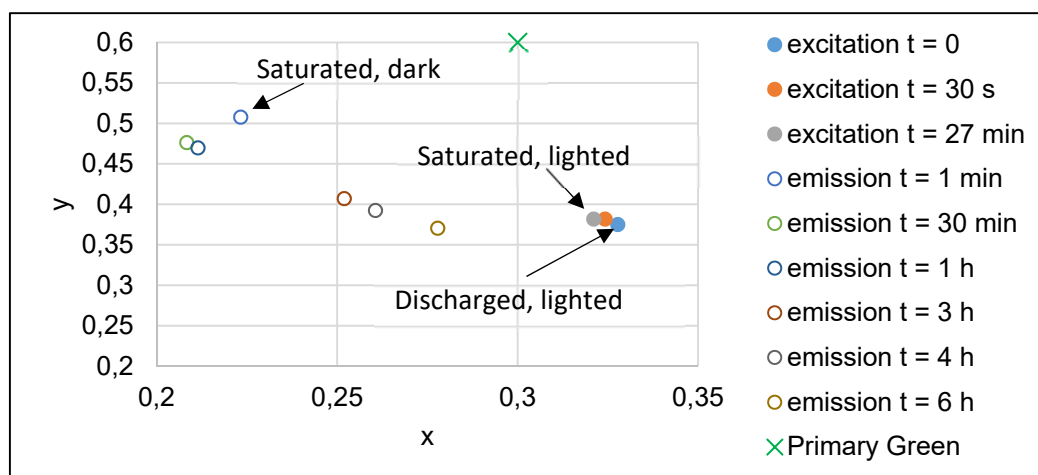


Figure 2 – Evolution of chromatic coordinates of a luminescent paint sample (S1) during an excitation/emission cycle.

3.2 Luminance measurements

3.2.1 Luminance measurement in the dark

Figure 3 shows the decay curves obtained in the laboratory with two samples (S3 & S4, see Fig. 1). The luminance of the white luminescent sample S3 (black curve in Figure 3), which meets the chromaticity requirements of the EN 1436 standard (CEN, 2018), decreases from 28.6 mcd/m² after one hour of emission in the dark to 7.2 mcd/m² after 3 hours, down to 1.6 mcd/m² after 10 hours. The luminance of the green sample (S4), which does not meet the chromaticity requirements of this standard, is two to three times higher (dark green curve in Figure 3).

In terms of durability, the decay curve of an area of the polished core (light green curve in Figure 3) after 180,000 passes is approximately 15% lower than that of the unpolished area (dark green curve in Figure 3).

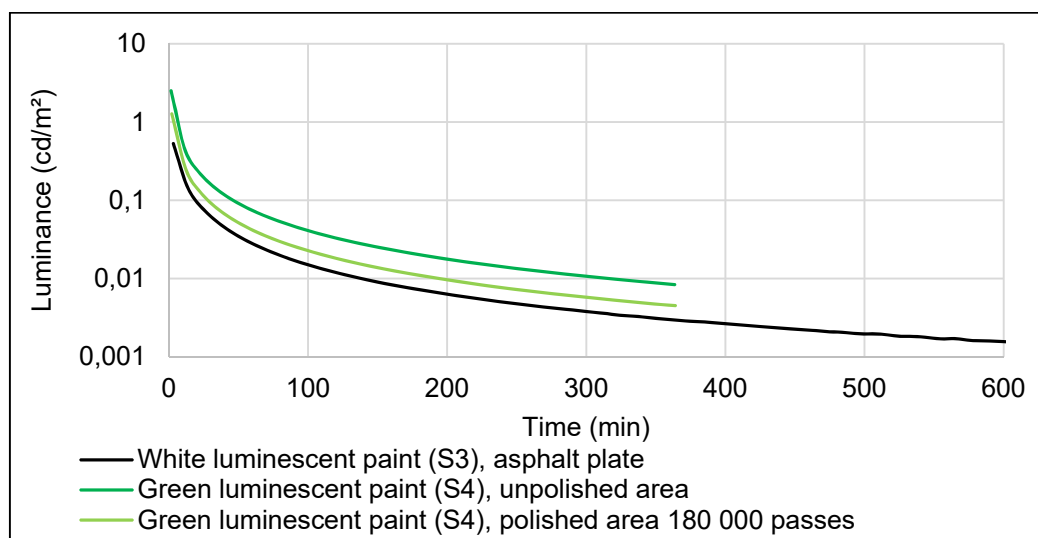


Figure 3 – Decay curves in the dark measured in the laboratory at 2.29° observation angle after 30' min of excitation under 1500 lx in a light booth (D65 illuminant + UV).

3.2.2 Luminance measurement under constant illumination (moon)

Table 2 shows the decay curve (under 0.1 lx and in the dark) of sample S1 deposited on an aluminium plate. As expected, the luminance during the emission under constant low illumination is higher than in the dark. The significant point is that the difference between the

two is stable over time, and proportional to the illuminance (for $E \leq 0.5$ lx). This difference, which corresponds to the luminance "bonus" specifically related to ambient lighting, can also be estimated by measuring, under this very low lighting, the luminance of the discharged sample (22.5 mcd/m^2 under 0.1 lx for sample S1, see Table 2).

Table 2 – Difference ΔL between the luminance (mcd/m^2) under 0.1 lx and in the dark during emission of sample S1 of luminescent paint deposited on an aluminium plate

Time (min)	Luminance decay under 0.1 lx (mcd/m^2)	Luminance decay in the dark (mcd/m^2)	Difference ΔL (mcd/m^2)
60	74,3	50,3	24,0
180	36,8	13,9	23,0
240	32,2	9,9	22,3
300	30,0	7,6	22,4
360	28,6	6,2	22,4
420	27,8	5,1	22,6

On a moonless night, the horizontal illumination on the roadway is around 0.01 lx (between 0.008 and 0.016 lx measured by the authors on a dual two-lane road in the open country). It increases during moonrise up to 0.03 lx or even 0.08 lx depending on the period (measurements carried out by the authors on the same dual two-lane road), and can reach 0.1 to 0.3 lx on a full moon night (Kyba, 2017). In addition, ground level illumination due to light pollution in overcast skies can reach levels similar to a full moon (Kyba, 2017). For sample S3 (Figure 1, center), an increase of 2.1 mcd/m^2 was measured under 0.01 lx , of 9.9 mcd/m^2 under 0.05 lx , of 19.5 mcd/m^2 under 0.1 lx and of 98.6 mcd/m^2 under 0.5 lx with respect to the decay curve in the dark. The offset (in mcd/m^2) is comparable to the luminance values of a Q5 traditional road marking with $Q_d=200 \text{ mcd/m}^2/\text{lx}$. The Q_d of this sample measured outdoor during daytime was $238 \text{ mcd/m}^2/\text{lx}$.

3.2.3 Luminance measurement under cyclic illumination (traffic)

The expected and observed effect of the periodic traffic on luminescence emission is an increase of luminance over time with respect to the decay curve in the dark. The increase is constant over time. In addition, this increase varies linearly with traffic density (Figure 4), and is inversely proportional to the simulated vehicles speed.

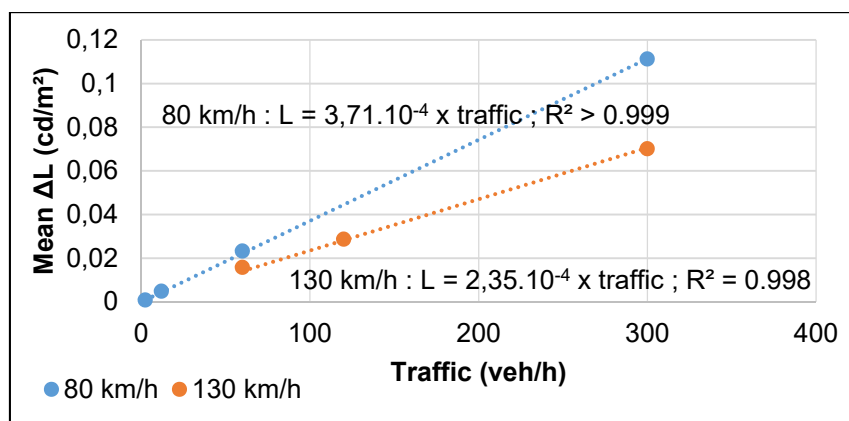


Figure 4 – Mean difference ΔL (cd/m^2) between the luminance in the dark with traffic and without traffic during the discharge of sample S2 of luminescent paint deposited on an aluminium plate depending on the simulated traffic (veh/h) at 80 and 130 km/h.

For the white luminescent sample S3 (Figure 1, center), an average increase of 10.9 mcd/m^2 was measured under a traffic of 120 veh/h at 80 km/h . In this case, the contribution of the simulated automotive lighting corresponds to an increase of 150% after 3 hours, compared to the emission in the dark.

3.3 Measurement in controlled environment on real road markings

Examples of decay curves obtained after two hours of simulated sunsets are shown in solid lines in Figure 5. As observed in laboratory measurement with other samples, the white luminescent marking (in accordance with the EN1436 requirement) emitted less luminescence than the green one. The measurements show small differences from one sunset to another, especially after several hours of emission in the dark ($< 10\%$ for white luminescent marking, $< 5\%$ for the green one). During the first two/three hours of emission in the dark, the luminance was lower after the darker sunset (up to 20% for the white luminescent road marking).

Note that the solid green curve was obtained with the same green paint pot (S4) as the core manually painted shown in Figure 1 (right). We see in Figure 5 that the luminance of the asphalt sample (dotted curve) is greater than that of the one measured in Sense-City (solid green curve). This can be due to the difference in application, in particular the lower and more realistic paint density in Sense-City, and to the lower horizontal illuminance, below 200 lx , received during the last half hour of excitation in Sense-City.

Finally, the measurements in Sense-City showed that the luminescent markings tested are brighter than a traditional Q5 class white marking ($Q_d = 233\text{ mcd/m}^2/\text{lx}$) during sunset, between 1h and 30 min before full darkness.

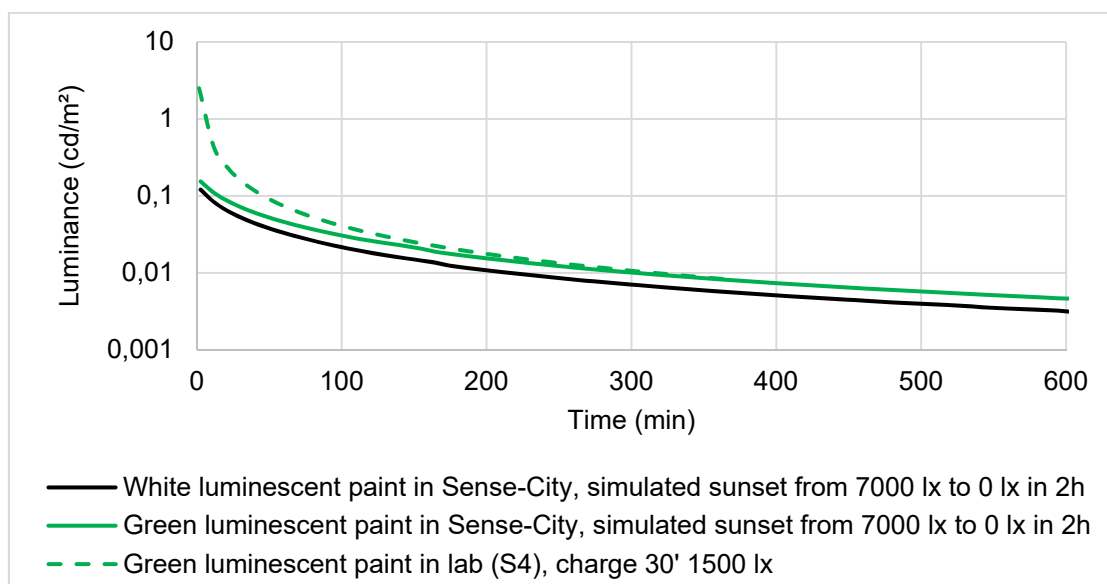


Figure 5 – Decay curves in the dark at 2.29° observation angle. Solid lines: in Sense-City after a simulated sunset from 7000 lx to 0 lx in 2h; Dotted line: sample S4 of the same green luminescent paint measured in laboratory 30' min of excitation under 1500 lx in a light booth (D65 illuminant + UV)

3.4 Visibility computations

From the laboratory measurements described above and the calculation method proposed in the COST 331 report (1999), the visibility distance of the luminescent marking beyond the range of the headlights was calculated, and compared to the visibility distance of a traditional retroreflective marking illuminated by conventional low beam headlamps. Our findings assume that the luminescent marking is equivalent to the traditional road marking in terms of retro-reflection (same R_L).

The luminance of the luminescent road markings was estimated from the decay curves computed from the measurements in the dark and from the offsets due to constant illumination and simulated traffic. The conclusions of our visibility computations depend on the considered luminescent samples, on the night-time ambient lighting, on the traffic and the assumptions used for comparisons (R_L & Q_d of traditional markings, type of headlights).

Under an ambient illumination of 0.01 lx and without traffic, a white luminescent marking (sample S3), which meets the chromaticity requirements of the EN 1436 standard (CEN, 2018),

could be visible between one and two hours after the start of the night in a straight line at a distance greater than the traditional marking (illuminated with low beam headlights). With sample S2, which does not meet the required chromaticity, this advantage could last between two and three hours under 0.01 lx and one hour under 0.1 lx. The visibility distance of a traditional road marking with high beam headlights is always higher than the one of a luminescent marking without headlights.

Traffic increases the visibility of the luminescent markings, but the benefit is very dependent on the night-time ambient illumination. Figure 6 shows the time during which a white luminescent road marking (sample S3, Figure 1, center) could be visible beyond the low beam headlights at a greater distance than a traditional retroreflective road marking ($Q_3 Q_d=130 \text{ mcd/m}^2/\text{lx}$, $R_4 R_L=200 \text{ mcd/m}^2/\text{lx}$). This “useful time” is given as a function of the traffic (in veh/h) at 80 km/h, for various illumination conditions and young and older drivers (20 and 60 years old).

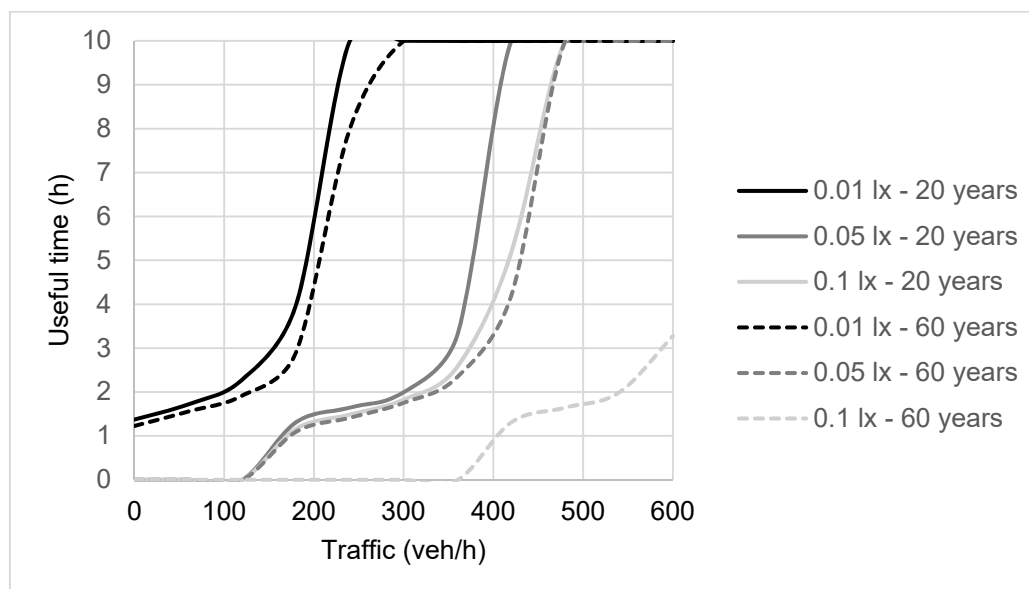


Figure 6 – Useful time (h) as a function of the traffic density (veh/h) at 80 km/h under 0.01 lx (black), 0.05 lx (dark gray), or 0.1 lx (light grey). The useful time is the time during which the visibility distance of a white luminescent road marking (S3) (beyond the low beam headlight) is higher than the one of a traditional road marking ($Q_3 Q_d=130 \text{ mcd/m}^2/\text{lx}$, $R_4 R_L=200 \text{ mcd/m}^2/\text{lx}$) in low beam headlights, assuming that both markings having the same R_L . Solid line: 20 year-old driver. Dashed line: 60 year-old driver.

According to Figure 6, the excitation from a traffic of 300 vehicles/hour, traveling at 80km/h with low beam headlights, allows a white luminescent marking to be visible during the first two hours of the night, or even all night under 0.01 lx, at a greater distance than the traditional marking taken as reference (see Section 2.3). The gain in visibility provided by luminescent marking is lower for the older drivers, but when the traffic is high enough, an increase of visibility distance beyond the headlights can improve their safety.

4 Conclusions

In this paper, a repeatable and simple laboratory measurement procedure on luminescent samples associated with visibility computations was proposed to characterise the performance of luminescent road markings. Our findings show that for equivalent performance in terms of R_L and Q_d , luminescent markings may strengthen the visual guidance of drivers on the road by increasing the visibility distance beyond the headlamps range under favourable night-time lighting conditions and with traffic. Depending on the conditions, the benefit may last a few minutes or the whole night through. Beyond the range of the headlamps, luminescent markings are of interest when the luminescence significantly increases the luminance of the marking compared to the reflection alone, which is possible in low light conditions on unlit roads. These conclusions are mainly based on measurements conducted on samples in the laboratory (dry

sample, controlled temperature, artificial polishing), or in a controlled environment (artificial sunset), and on the visibility calculations carried out with the COST 331 method.

Some assumptions in our computations are questionable. The visual adaptation level does not take into account the headlamps in the computation of the visibility distance beyond the headlight beams. In addition, we assumed that the luminescent marking are retroreflective, while our computations were based on luminance measurement of a non-retroreflective sample (R0 class). Findings need to be confirmed with homologated retro-reflective luminescent road markings.

Measurements in laboratory conditions differ from real situations. On the one hand, the simulated scenarios are simplified, and in particular, the excitation phase of the products is somehow conventional, not directly related to what happens during the day and twilight. As highlighted with our measurements in the Sense-City full scale mock-up, the lower illuminance at the end of the sunset leads to a lower luminescence in the first hours of darkness. In addition, light sources used in the laboratory excitation can be discussed. Especially, our simulation of night-time illumination could be improved using another, more realistic, spectral power distribution. Similarly, the traffic simulation may have overestimated the effect of traffic, as actual headlamps may use either LEDs or halogen sources; the latter contains less exciting short wavelengths. On the other hand, it is questionable whether the performance measured on (roller paint) samples produced in laboratory represents the performance of paints applied with a controlled density on the pavement with dedicated machines.

Our findings need to be confirmed by more systematic on-site measurements, under different conditions (e.g. temperature, humidity). Therefore, the experimental deployment of these products on experimental sites, and *in situ* monitoring methods will provide an improved feedback on performance whatever the external conditions and wear. Others scenarios could also be investigated, such as cycle paths and urban and road lighting.

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INFLUENCE OF ROAD SURFACES ON THE CALCULATION OF A TARGET VISIBILITY TAKING INTO ACCOUNT THE DIRECT AND INDIRECT LIGHTING

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Abstract

Street lighting ensures visibility and legibility for road users. In this paper, performances of the lighting installation of four road sections with different type of road surface are simulated in accordance with guidelines and road lighting standards. Then, the calculation of the visibility level of a target according to the Adrian's model is included. Next, the light reflections on the road surface are added to the calculation of the target luminance. For this, the area considered in front of the target as well as the number of elementary surfaces are fixed and a Q_0 -scaling of the r -table obtained for $\alpha = 45^\circ$ is performed. We compare the results obtained for each section with and without considering the light reflections and conclude that there is negligible incidence of the nature of the road surface on the target luminance. However, an effect of the road surface on the visibility level of the target is observed.

Keywords: Road Lighting Calculation, Road Surface, Visibility Level, Road Surface Reflections Properties.

1 Road lighting basics

Guidelines (CIE, 2019) and road lighting standards in Europe (CEN, 2015) define the performance requirements that are specified in the form of lighting classes for street lighting. They consider the visual needs of road users and the environmental aspects of street lighting. They specify the mathematical conventions and procedures to be adopted for calculating the photometric performance of public lighting installations.

Especially, they give threshold minimum values for illuminance and luminance and their distribution on the road surface according to a grid of points whose number N depends on the pole spacing S and the number of traffic lanes (Figure 1a).

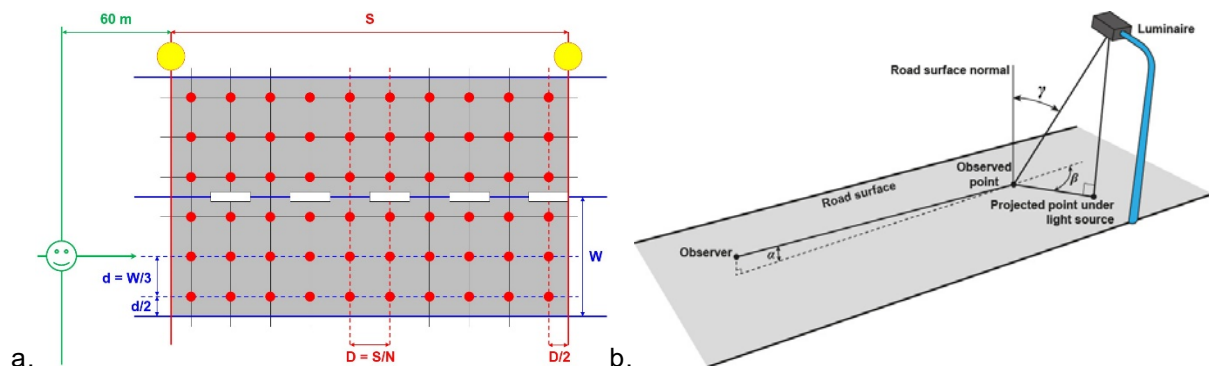


Figure 1 – a) Example of a calculation grid points (in red) in road lighting design, according to the European standard (CEN, 2015). The “smiley” represents the eye of the driver, W is the traffic lane width, d is the transversal distance between two rows of points and D is the longitudinal distance between two columns of points. **b)** The photometric characteristics of the road surface depend on the angles of observation α , deviation β and incidence γ .

Moreover, the reflection properties of the road surface are used for the computation of a lighting installation, in particular r -table. The r -table is a two-dimensional array with a number of standardized combinations of the incidence lighting angle γ and deviation angle β (Figure 1b), and their boundaries define a solid angle Ω_0 . To obtain it, the angle of observation α is set to 1° , which corresponds to a driver looking at about 86 m (CIE, 2001), and the luminance coefficient q is measured for all the combinations of β and γ .

The luminance coefficient q of a surface element in a given direction, under specified conditions of illumination is defined by

$$q(\beta, \gamma) = L(\beta, \gamma) / E_h \quad (1)$$

where L is the observed luminance in cd/m^2 and E_h the horizontal illuminance in lux.

The reduced luminance coefficient r is defined as:

$$r(\beta, \gamma) = q(\beta, \gamma) \times \cos^3 \gamma \times 10^4 \quad (2)$$

To simplify the description of photometric performance of road surfaces, the additional parameters Q_0 and S_1 can be calculated from the r -table as following :

$$Q_0 = \int_0^{\Omega_0} \frac{q(\beta, \tan \gamma) d\Omega}{\Omega_0} \quad (3)$$

Q_0 is the solid angle weighted average of all the luminance coefficients also called lightness (van Bommel, 2015) and the specularity factor S_1 (also called shininess), is given by:

$$S_1 = \frac{r(\beta = 0, \tan \gamma = 2)}{r(\beta = 0, \tan \gamma = 0)} \quad (4)$$

The CIE has defined different sets of standard r -tables that are directly available in all lighting design software (CIE, 1984). Since 2001, the CIE 144 (CIE, 2001) recommends a scaling of the chosen standard table according to the lightness Q_0 . It is obvious that the design of a road lighting system should be based on the knowledge of the actual luminance coefficient for the actual road. But, as the actual quantity q is generally not known, designers use in the calculations as q reference values the ones given in CIE 144 publication. In France, the CIE r -tables type R are mostly used (Muzet, 2019).

2 Computational setup and addition of Adrian's Visibility model

To go further than the classical photometric quantities (average luminance, overall and longitudinal uniformities), in our opinion, a visibility calculation is a necessary complement, especially since one of the main functions of lighting is to make an obstacle on the road visible and thus enable a user to avoid it. We propose to use Adrian's well-known visibility model for road lighting applications, a model that was included in the CIE documents a few years ago and then removed.

2.1 Computational setup

The computational scene represents an experimental site located on a suburban road (Boulevard Schuman) in Limoges, France (Muzet, 2018). This is a 2 x 2 lanes road 6.50 metres wide and 400 metres long. The 4.25 metres wide central reserve is equipped with a 9 metres high lighting system with twin central arrangement. The road surfacing of the entire Boulevard Schuman is a very thin asphalt concrete with a 0/10 mm gradation. The computational zone consists of two sections of 200 metres on either side of the boulevard (Figure 2). Section 1 and 2 are the innovative sections called Lumiroute® sections and section 3 and 4 are ordinary control sections. Sections 1 and 4 are raw sections while the surfaces of sections 2 and 3 are treated with high-pressure water jet to remove the thin bituminous layer from the surface. The road surface photometry of each section was characterised with the r -tables measured with the Cerema laboratory gonireflectometer (Muzet, 2019) and are shown in the Table 1.

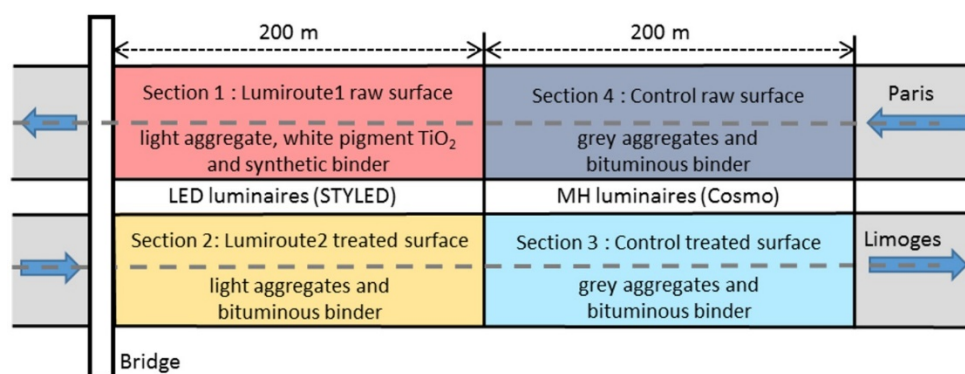
Table 1 – Photometric measurements with Cerema laboratory gonireflectometer: average values of Q_0 and S_1 .

	Section 1: Lumiroute® 1	Section 2: Lumiroute® 2	Section 3: Control Treated	Section 4: Control Raw
Q_0	0.1616	0.0864	0.0692	0.0649
S_1	1.0437	0.5236	0.8567	2.6095

The “control sections” 3 and 4 composed of ordinary road surfaces are lit by metal halide lighting while the two Lumiroute® sections composed of light surfaces are lit by adjustable LED lamps. Since the lighting arrangement is a twin central type, the luminaire spacing was the same for the Lumiroute® 1 and 2 sections. For section 2, a power demand of 103 W was necessary to comply with the 0.70 specification for longitudinal uniformity of ME3a class; the resulting luminaire spacing was 30 m. For the section 1, with a spacing of 30 m, a power demand of 77 W was necessary, resulting in an important overprovision of average luminance (1.83 cd/m² instead of the 1.11 cd/m² required for class ME3a).

The resulting four combinations of road surface and lighting are summarised below:

- Section 1 is composed of the Lumiroute® 1 road surface (raw surface with light-coloured aggregates, a synthetic binder and white pigment TiO₂) combined with a LED illumination of 77 W (STYLED lamp, colour temperature 4000 K).
- Section 2 consists of Lumiroute® 2 road surface (water jet scrubbed road surface with light aggregates and a bituminous binder) combined with a LED illumination of 103 W (STYLED lamp, colour temperature 4000 K).
- Section 3 is composed of a “Control treated” road surface (water jet scrubbed road surface with grey aggregate and a bituminous binder) combined with traditional lighting consisting of a 140 W metal halide discharge source (COSMO lamp, colour temperature of 2811 K).
- Section 4 is composed of a “Control raw” road surface (current road surface with grey aggregate and a bituminous binder) combined with the same 140 W metal halide discharge source.

**Figure 2 – Framework of the implementation of the four sections on the Boulevard Schumann in Limoges, France**

2.2 Adrian's model of Visibility Level

From 1972 to 2010, a supplementary criterion to those specified in the CIE performance requirements was used: the Visibility Level (VL). We will focus on the model of Adrian who adapted it for road applications in order to characterise a lighting installation quality.

The visibility calculation model presented by Adrian (Adrian, 1989) draws on laboratory research of Blackwell (Blackwell, 1946) and Aulthorn (Aulthorn, 1964). He defines the VL as

the ratio of the actual contrast C of a target with its background over a threshold contrast C_{th} (eq. (5)).

$$VL = \frac{C}{C_{th}} = \frac{\Delta L}{\Delta L_{th}} \quad (5)$$

where ΔL is the actual luminance difference in cd/m^2 , ΔL_{th} is the threshold luminance difference in cd/m^2 .

The calculation of the threshold luminance difference is based on two laws: Ricco's and Weber's (eq. (6)).

$$\Delta L_{th} = 2,6 \left(\frac{\Phi^{\frac{1}{2}}}{\alpha} + L^{\frac{1}{2}} \right)^2 \times AF \times TF \times F_{CP} \quad (6)$$

where α is the angular size of the target in minutes of arc, Φ is a luminous flux function that determines perception, characteristic of the Ricco's process, L is a luminance function, translating Weber's law.

Adrian used some factors in this formula (eq. (6)) to take into account the impact of the observer's age (AF), the observation time (TF) and the contrast polarisation (F_{CP}) on the visibility of a target in an illuminated road (defined in (Adrian, 1989)). Moreover, he replaced the background luminance by an adaptation luminance to consider the presence of glare sources in the visual field.

2.3 Computational calculations of Visibility Level

A specific software was developed for this study. It computes the performance of a lighting installation in accordance with (CEN, 2015) and (CIE, 2019). It takes into account the measured photometry of road surfaces and luminaires. In addition, Adrian's model of visibility level is implemented.

For each of the four sections, the average luminance (L_{ave}), the overall luminance uniformity ratio (U_0) and the longitudinal luminance uniformity ratio (U_l) are computed according to standard specifications. To calculate the VL, a square target is placed vertically in every point of the CIE calculation grid. The target is $25 \text{ cm} \times 25 \text{ cm}$ and has 20% diffuse reflectance. The VL is first computed considering only direct illuminance (Figure 3.a.). For the background luminance, the luminance on the side of the target that maximises the contrast is used because it was shown in a comparison between contrast computation and human detection (Brémond, 2011) that it is better correlated to target detection performance.

The results are summarised in the Table 2. For the VL, the average, minimum and maximum of 60 grid points are computed.

Table 2 – Performance calculations considering only direct illuminance for each section when the observer is in fast lane (Lane 1) or in slow lane (Lane 2)

Section	Lane	L_{ave} (cd/m^2)	U_0	U_l	$ VL _{ave}$	$ VL _{min}$	$ VL _{max}$
1	1	1.89	0.49	0.87	25.58	8.81	50.90
	2	2.08	0.49	0.84	27.53	10.46	49.15
2	1	1.47	0.65	0.83	19.00	6.79	31.34
	2	1.52	0.67	0.88	19.63	7.82	29.27
3	1	1.32	0.69	0.79	13.89	0.39	22.33
	2	1.41	0.73	0.79	14.82	1.04	23.80
4	1	1.32	0.45	0.82	15.22	2.27	38.39
	2	1.53	0.50	0.81	17.10	1.20	37.86

3 Addition of light reflections on the road surface

3.1 Calculation of the reflected illuminance arriving on the target

In order to study the influence of the road surface on the target visibility, we complete our method of calculation taking into account the indirect illumination due to the light that arrives on the target after reflection on the road surface. In fact, the luminance of the target is the result of two components: the direct light from the luminaires and the light reflected off the road surface in front of the target (Figure 3.a.).

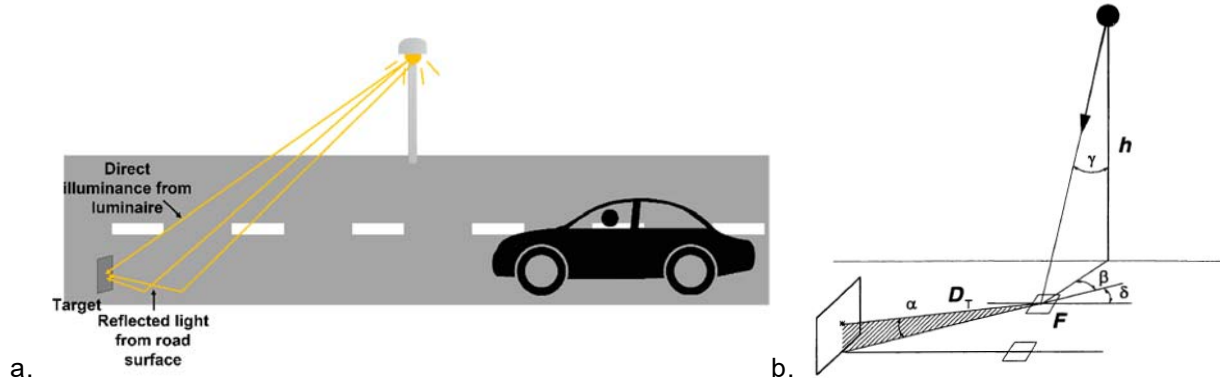


**Figure 3 – a. Sources of target luminance.
b. Geometry for the indirect target illuminance calculation (Gibbons, 1998)**

Then, the overall vertical illuminance of the target E_T is the sum of a direct component E_{TD} and a reflected component E_{TR} (eq. (7)).

$$E_T = E_{TD} + E_{TR} \quad (7)$$

Considering a small portion of the road surface as a light emitting source, according to the geometry shown in Figure 3.b., the reflected illuminance arriving on the target is (Gibbons, 1998):

$$E_{TR} = \frac{I_s}{D_T^2} \cos \alpha \cos \delta \quad (8)$$

where I_s is the intensity emitted from the road surface, D_T is the distance from the road portion to the target, α is the angle of the reflected light upward, δ is the angle of the reflected light to the normal of the target surface.

The intensity I_s of the light coming from the portion of the road would be:

$$I_s = L_p \times F \times \sin \alpha \quad (9)$$

where L_p is the luminance of the road surface and F is the area of the elementary surface.

3.1.1 Integration area and number of elementary surfaces

As we can see in equations 8 and 9, the reflected illuminance arriving on the target depends on the area of the road portion and its distance to the target. To obtain the total reflected illuminance on the target, all the road surface in front of the target must be integrated. As the reflected illuminance has an inverse dependence on the square distance (see eq. (8)), the further away the road is, the less it contributes. In order to avoid having an integration zone that exceeds the road width, especially for points located at the edge of the lane, we choose an area of $1 \text{ m} \times 1 \text{ m}$. This makes a road surface area of sixteen times the target area that is in accordance with Gibbons's suggestions in his thesis, i.e. to take a minimum area of nine times the target area (Gibbons, 1998).