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Road Surface Photometric Characterisation and Its Impact on Energy Savings

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Abstract: How road surfaces reflect light in space is a physical characteristic that plays a key role in the design of road lighting installations: by European Standards the average luminance is the target quantity to assure the required safety conditions of the motorized road traffic. Lighting systems are designed (luminous flux installed per kilometre) to comply with the above requirement, starting from reference values of road surfaces reflection published in an old scientific document. These data are obsolete and not representative of current road surfaces, but they are still used to design current LED lighting systems. European Community funded a SURFACE project to provide to EU standard organization new traceable reference data, representative of current road surfaces used in EU. The paper presents the data collections and the impact on road lighting of using available old reference data versus SURFACE collected data of current road surfaces. Results highlight advantages in using bright pavements as well the need for introducing systems for flux control in road lighting installation to compensate for the discrepancies between current reference data and actual road surface data.

1. Introduction

Pavement surface characteristics are crucial for functional quality and safety of roads, related not only to its mechanical and dynamic performance, but also to its visual performance and the safety at night of all road users. In Europe there are 5 Million kilometres of roads [1], about the 40% of them are lit, according to three different European countries Road National Administrations, by lighting systems designed considering photometric performance of pavements published in a technical documents of the 1970s [2]. Currently, road lighting plants must comply with the directives of the European Road Lighting Standards [3] to [4]. A CIE document [5] specifies the most important lighting parameters (and traffic related parameters) for different road environments like: motorised traffic areas (M lighting class), conflict areas (where vehicle stream intersect or run in areas frequented by weak users, C lighting class), and pedestrian and low speed areas (P lighting class). The CEN technical report [6] gives guidelines on the selection of the most appropriate lighting class, but leaves to national policy the decision on the criteria to assign a road to a given lighting class. The EN standard [3] specifies, for every lighting class the photometric requirements to satisfy visual needs of the different users. For motorized road (M lighting class), the relevant lighting criteria are based on road surface luminance (def. 845-01-45 in [7] is the quantity perceived by the human eye, i.e., the luminous flux

emitted (or reflected) by a surface as observed in a given direction). For C and P lighting classes, the relevant photometric parameter is the illuminance (def. 845-01-38 in [7] quantity of light falling on a surface).

However, [6] states luminance as the recommended criterion for C lighting class too, illuminance requirements are *"for use when the convention for road luminance calculations do not apply or are impracticable"*. Moreover, the CEN document provides the correspondence between luminance and average horizontal illuminance for conflict area C lighting class. In a real environment, C and P lighting classes are strongly related to M lighting class: P class requirements apply [3] for areas *"lying separately or along the carriageway of a traffic route"* or low speed (<40 km/h). This last requirement for speed is considered in the M lighting class too. Standard [3] for the M lighting class specifies the average road luminance overall uniformity and the longitudinal uniformity that must be maintained by the lighting system in order to ensure safety and proper visibility condition for the assigned lighting class to all road users. The road luminance is calculated from a physical property of the pavement describing its reflective behavior: the luminance coefficient, q (or reduced luminance coefficient r, the q values multiplied by the cube of the cosine of the angle of light incidence) and from the luminous intensity emission (in a given direction) of road lighting luminaires. Obviously, luminaires generate an illuminance on the road surface, but this is not the relevant quantity to describe neither the quality nor the compliance with safety visibility criteria of a road lighting system for M lighting class.

Considering the physical pavement property, the luminance coefficient q of the road links the illuminance (linearly proportional to energy consumption) with the luminance related to the visual performance, described by a vision model which defines the luminance values required to recognize obstacles on the road. The latter is not linearly linked to the energy consumption.

Designers determine the required number and spacing of road luminaires in a road to fulfil the requirements for road luminance and quality parameters values, given in the EN Standard [4] with the additional goal of energy optimization. Because in town areas M lighting class strongly relates with P and C classes too, number and spacing of luminaires poles are according to calculations of M class and if necessary, additional requirements for P (footways, cycleways,...) and C class (mainly used for parking areas or bus stops, if luminance requirement is impracticable) must be satisfied too. To do these calculations based on luminance criterion, designers use reference data of r values (called r-tables) published in the CIE 144 document [2]. However, these r-tables are derived from measurements carried out more than 40 years ago. The photometric properties of the road materials have evolved over time [8–13] and reference data is not available for all geometrical conditions defined in the current standards for lighting calculations. Furthermore, the reliability of the data is unknown, because no statement about measurement uncertainty is presented.

The energy consumption in Europe used for lighting amounts to 14% of the total energy consumption (data from 2011) [14]. This is the reason for the large impact on energy savings achievable with suitable actions on lighting. For road lighting, actions should start already at the design stage, by the use of more reliable and optimized q data as well as design methods specific for smart lighting.

The introduction of energy performance indicators into the European standard [4] and its correlated requirements pushed forward the optimization of the lighting system, not only in the design of luminaires and in the selection of their luminous intensity distribution, but also in the installation layout and in obtaining and maintaining the lighting level at the minimum value required by the standard. This last aspect can be solved by the use of adaptive lighting systems equipped with a luminance measurement system: a continuous monitoring of the road luminance can reduce the energy consumption to a minimum. The energy optimization requires reaching the luminance prescribed by road lighting standards with the lowest energy consumption. The advantages are not only in energy usage, but at lower illuminance the luminous flux reflected by the illuminated surfaces (road, buildings and grass, etc.) will be lower too, therefore the sky luminance (i.e., the lighting pollution) will be reduced.

However, there is a downside in the design procedure that makes the whole standardization structure for energy saving ineffective: lighting designers tend to over-dimension the installed flux, because they are well aware that the *q* and *r* data currently used in calculations are derived from measurements carried out more than 40 years ago. These values are not adequate for designing against requirements of vision performance, optimisation and energy consumption of modern lighting installations for several reasons:

- The properties of current pavements have progressively changed, and some studies show that using the current standards, based on available CIE data, may lead to errors on average luminance often over 30% and sometimes over 50% [15]. Moreover, the photometric properties of the road materials can change significantly over time [10,16].
- New types of luminaires, especially those using SSL, have very sharp luminous intensity distributions; this simplifies the energy consumption optimisation but increases the influence of the road surface reflective characteristics, especially when luminance and/or uniformities are considered.
- SSL including current LED technology supports smart lighting, and the ability to adapt the flux at any time, in terms of both intensity and direction, according to the brightness requirements and specifics of the road pavement.

It is necessary for the road lighting community to obtain new reliable standard reference values representative of present-day pavement reflectance (*q* and *r* values) with assurance of traceability of measured data. For these reasons the EU Community funded the EMPIR SURFACE project [17] with the goal to establish a metrological chain for the measurement of *q* and *r* values and to provide to the European standardization body new reference tables of *q* and *r* values for currently used pavements. This paper presents a comparison between reference data of CIE144 and *r*-tables of representative pavement surfaces measured in laboratory on samples from all over Europe and their impact on the road lighting design for typical road lighting installation layouts, e.g., those in [4].

2. Materials and Methods

2.1. The Road Luminance Coefficient

As previously stated, the design of a road lighting system is made starting from the luminous intensity distribution of a given luminaire and the luminance coefficient of the road surface. The luminance coefficient (*q*) of a surface element in a given direction, under specified conditions of illumination is defined in [7] def. 17-712 as *quotient of the luminance of the surface element in the given direction by the illuminance on the medium*:

$$q = \frac{L}{E} \qquad (1)$$

where:
q is the luminance coefficient measured in $[\text{sr}^{-1}]$;
L is the luminance measured in $[\text{cd}/\text{m}^2]$;
E is the illuminance measured in [lx].

To simplify the description of photometric performance of road surfaces, the additional parameters q_0 and S_1 can be calculated from the full table of *q* values, where q_0 represents the diffuse behaviour and S_1 the specular behaviour. While, as used in the following, Q_0 is the solid angle weighted average of the *q* values of a pavement.

It is obvious that the design of a road lighting system should be based on the knowledge of the *actual* luminance coefficient (in the direction of emission of road lighting luminaires and the direction of observation) 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 [2]. These values have been established from measurements on several road surfaces made in the mid 1970s and are obviously not representative of current road surfaces nor have uncertainty values associated with the measured values. The low reliability of the available *q* data is well known: to be sure to reach the luminance standard requirements and avoid controversy with the customers, designers introduce an heuristic over-dimensioning of the installed luminous flux which compensates for the supposed depreciation due to ageing. This approach has been adopted for several years and it worked well when the energy saving and optimization of the installation was not considered. Previous studies [15,18] showed that this heuristic approach together with the use of old data, may lead to errors on average luminance, calculated against those measured on site, often over 30% and sometimes over 50%.

In annex C of [4], i.e., an annex in a standard to be considered only informative and not compulsory, there is an interesting quantity for the evaluation of energy performance: the *Installation lighting factor* (q_{inst}) of the system.

$$q_{\mathrm{inst}} = \frac{\overline{L}}{\overline{E} Q_0} \tag{2}$$

where:
$\overline{L}$ is the calculated averaged maintained road luminance [cd/m^2];
$\overline{E}$ is the calculated averaged maintained road illuminance [lx];
Q_0 is the average luminance coefficient of the selected road adopted in calculation during the road lighting design.

The *Installation Lighting factor* characterises the energy performance of a lighting installation at different steps:

- At the analysis stage, e.g., through the classification of the luminaires in standardised environments,
- At the synthesis, allowing the design of lighting installations with predictable energy savings,
- At the final on-site verification stage, the agreement with prescriptions based on q_{inst} permits to easily declare the compliance with the standards and energy savings

A high value of q_{inst} characterises installations with high energy savings, q_{inst} usually has values ranging from 0.8 to 1.3: an increase from 0.8 to 1.3 gives a 40% decrease of the power density indicator D_P [4]. The quantity q_{inst} allows easy comparison of energy performance of luminaires in different installations.

2.2. Energy Performance Indicators

The energy performance indicators [4] force further optimization, recognizing the direct link between energy consumption and illuminance on the road surface, but give also too much relevance to illuminance which is not the quantity related to road safety. The *Power Density Indicator* is an energy performance indicator defined in [4] (in the normative part, in contrast to the previous quantity) as "*the total power of the road lighting installation divided by the value of the product of the surface area to be lit and the calculated maintained average illuminance value*" on the area.

$$D_{\mathrm{P}} = \frac{P}{\sum_i \overline{E}_i A_i} \tag{3}$$

where:
P is the total system power, in [W], of the lighting installation calculated as sum of the operational power of every lighting point (P_k) and of the operational power (P_{ad}) of all devices necessary for the operation of the lighting system: $P = \sum_k P_k + P_{ad}$;

A is the lit relevant area in $[m^2]$;
$\bar{E}_i$ is the maintained average horizontal illuminance, in [lx], of the sub-area A_i.

Another energy performance indicator defined in [4] is the *Annual energy consumption* D_E that is the ratio between the product of the operational power of the lighting plant for the time of operation over the size of the lit area.

$$D_E = \frac{\sum_j P_j t_j}{A} \tag{4}$$

where:
P_j is the total system power, in [watt], of the lighting installation in the j-th period of time;
A is the lit relevant area (in $[m^2]$);
t_j is the period of time when the power P_j is consumed and is measured in [h].

Obviously the *Annual energy Consumption*, depends on factors characterizing the lighting system, like the source luminous efficiency, but for a given lighting plant, depends also on seasonal variations of daylight, traffic fluxes, and weather conditions when the lighting system is associated with smart controller. EN 13201 [4] suggests, for assessing the energy performance of a given lighting system, to present and use together the two aforesaid indicators D_P and D_E.

It is convenient to recall the essential criteria for saving energy in lighting installations: apart from the obvious suggestion to use luminous sources with the highest efficiency, the Power density indicator should be minimized, provided that safety is ensured. The *Power density indicator* value derives from two main entries: the generation and the distribution of the luminous flux (related to luminous sources and luminaires and their installation positions) and the connection between road illuminance and luminance (luminous intensity distribution and type of road pavement). As pointed out, it is common to over-dimension the system because the average luminance must be maintained during the whole life of the installation.

The knowledge of the actual road characteristics is also important in order to understand differences between on-site measurements and design calculations [19]. If these are greater than the measurement uncertainty (of a measurement) and/or than the results of the tolerance analysis (of a calculation) then the reasons for these discrepancies shall be analysed. After simple preliminary checks, the measurement of the road surface reflectance is a good starting point of investigation because, up to now, it has the lowest level of reliability. SSL luminaires may have very sharp luminous intensity distribution; this simplifies the calculation for optimization of the energy consumption but increases the influence of the road surface characteristic in reflection, especially when the luminance uniformity is considered.

2.3. Design and Calculation of the Road Luminance Values

The road luminance calculations are based on the following formula that provides the relationship between the luminance coefficient and a given incidence direction (α, ϵ), shown in Figure 4 of [20] which provides the "*Angular relationships for luminaire at tilt during measurement, observer, and point of observation*" and also here in Figure 1

$$q(\alpha, \epsilon, \beta) = \frac{L(\alpha, \beta + \frac{\pi}{2})}{E(\epsilon, \beta)} \tag{5}$$

where:
$q(\alpha, \epsilon, \beta)$ is the luminance coefficient of the road surface [7] measured in reciprocal steradians;
$(\alpha, \epsilon, \beta)$ are the angular coordinates of the incident light path (ϵ, β) and the view direction α shown in Figure 4 of [20] and in Figure 1;

$L(\alpha, \beta + \frac{\pi}{2})$ is the luminance of the road surface as viewed in the direction $(\alpha, \beta + \frac{\pi}{2})$;
$E(\epsilon, \beta)$ is the illuminance on the lighted elementary road surface considering the incident light path with angular coordinates (ϵ, β). Standards [20] consider the angle of observation of the road surface α, constant and sets $\alpha = 1°$.

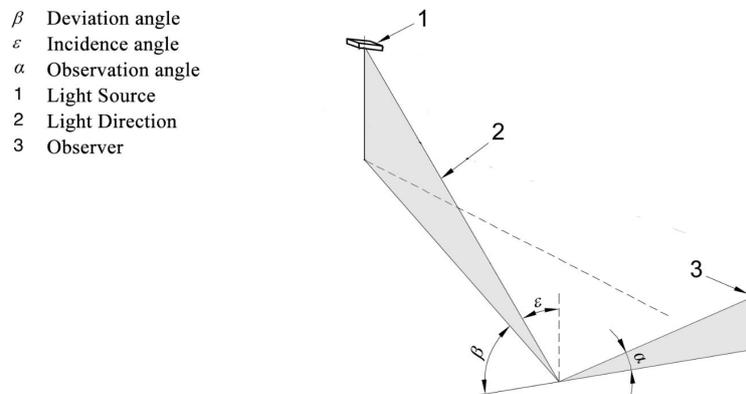|	
β	Deviation angle
ϵ	Incidence angle
α	Observation angle
1	Light Source
2	Light Direction
3	Observer

Figure 1. Relevant angles in road lighting design.

Equation (5) can be rewritten, considering only one luminaire and its normalized luminous intensity distribution I_n, as:

$$L = \frac{I_n(C, \gamma)\Phi q(\epsilon, \beta)cos^3\epsilon f_M}{H^2} \tag{6}$$

where:
L is the luminance at the point on the road;
$I_n(C, \gamma)$ is the normalized luminous intensity of the luminaire at a direction specified by the angular coordinates (C, γ), in [cd/lm];
$q(\epsilon, \beta)$ is the luminance coefficient for the incident light path with angular coordinates (ϵ, β) ;
Φ is the luminous flux of the luminaire, in [lm];
f_M is the luminaire overall maintenance factor, unit 1;
H is the mounting height of the luminaire above the surface of the road, in [m].

The definition of the normalized luminous intensity distribution is very useful because:

- the manufacturing tolerances of a luminaire are generally given considering the rated luminous flux and a nominal luminous intensity distribution;
- luminaires with flux control can work at the rated luminous flux while their luminous intensity distribution may change with aging;
- it helps to identify photometric contribution (luminous flux) and geometric contribution (direction of lighting) that depend on mounting tolerances (mounting height of the luminaire, inter-distance between poles, rotation, orientation and tilt of the luminaire);
- tolerances on the luminaire luminous flux and on the luminous intensity distribution may arise from different physical causes: for example, in traditional luminaires, the luminous flux of the source and the source position with respect to the reflector focus, or in LED luminaires, the total luminous flux and the ratio between the luminous flux of the single chips or the mechanical position of the LED module;
- luminaire aging may independently modify the luminous flux value and the normalized luminous intensity distribution.

Regarding the different components in Equation(6) the photometric values related to the luminaire emission (flux and normalized intensity distribution) have high reliability: the metrological chain of photometry of luminaires is well established. Also, regarding the mounting height, there is little

concern regarding tolerance. However, regarding the q values the aforementioned problem remains: old data is not representative of current surfaces and an uncertainty statement is lacking.

2.4. SURFACE Project and Its New Data Collection

It is now clear that the values of q used in the design stage represent an important point for correct design of road lighting and therefore for a fruitful energy saving. In order to establish a European metrological chain on the measurement of q it is necessary to take action coordinated among the NMI of EU. Only few NMIs perform road lighting research and at the same time have facilities and capabilities for road material characterisation. These NMIs support road lighting research but singularly and at national level: there is the need for a coordinated NMI action. Within the Horizon 2020 research and innovation programme is EMPIR programme, co-financed by the EURAMET [21], participating states, and the Horizon 2020 programme. The EMPIR programme funds the project "*16NRM02 SURFACE, Pavement surface characterisation for smart and efficient road lighting*" [17] with the task of defining new reference data of q with an associated uncertainty statement representative of current road surfaces and establishing the metrological chain on the q quantity. The SURFACE consortium is constituted by all EU NMIs performing metrological research on road lighting in Europe (INRIM Italy - project leader, AALTO Finland, LNE France, METAS Switzerland, METROSERT Estonia, RISE Sweden), plus the National French Research Centre Cerema, and two industrial partners focused on software simulation (OPTIS-ANSYS) and portable instruments (Zehntner – ProceQ). One of the goals of SURFACE is to provide to CEN new r-tables with stated uncertainty, based on currently used road surfaces to be used in the future at the road lighting design stage. These data will be based on a large data collection of the different road surfaces used in Europe that the consortium is collecting among stakeholders. To achieve this goal, the SURFACE project launched a call during CIE events on road lighting, e.g., the Road Surface workshop during the CIE Mid Term meeting in Korea [22] and during CIE Expert symposium on road visibility [23]. Currently the SURFACE database considers only measurements made after 1990 and only by laboratory goniophotometer, so no measurements from portable devices at a reduced set of angles are included. Unfortunately, it was not easy for SURFACE to collect data because only few European laboratories are doing this type of measurements and because of confidentiality obligations. For confidentiality, each r-table collected is still the property of the provider, the SURFACE consortium has made the commitment of not distributing nor publishing the single r-table data but is allowed to manage and make use of them in order to provide the reference r-table to CEN. It means that the reference data for CEN will not consist of an identifiable r-table , but it will be just a representative average. The collection of data is now composed of:

- 40 r-tables from Switzerland;
- 182 r-tables from France;
- 18 Q_0 and S_1 factors from Finland.

Unfortunately, r-tables from other European countries is to-date not available.

The CIE standard r-tables data, used presently at the design stage of road lighting systems, is shown in Table 1, with the indication of the EU country that adopted it as national reference for road lighting calculation. CIE standard r-tables are based on an old database [24] of 285 measurements done around the mid-1970s (1975) on samples mostly from the Nordic countries. In the SURFACE database, there are now 240 measurements. For this study, we only considered the stabilised pavements (more than two years old) to exclude initial specular effect. This excludes 102 tables from France (new or 1-year measurement). So our final data set is composed of 138 Q_0 and S_1 factor (40 from Switzerland, 79 from France and 18 from Finland). This database is composed of 6 cement concretes, 6 pavements with synthetic binders, and 126 bituminous concrete. Figure 2 compares Q_0 and S_1 values of the original 1975 database with the CIE reference r-tables and the current SURFACE database composed of 138 stabilised pavements (in orange).
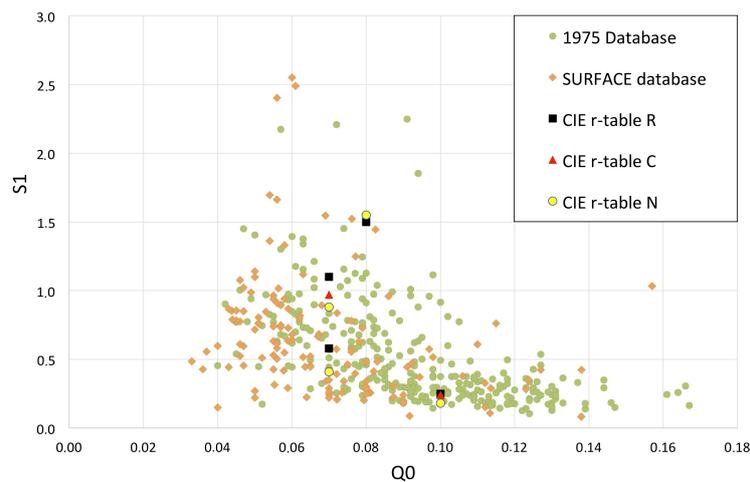
Figure 2. Q_0 and S_1 values of the original 1975 database, CIE road surface reference r-tables and the current SURFACE database composed of 138 stabilised pavements.

Considering the data in Figure 2, recent pavements seem to have lower Q_0 than the old data. This result is consistent with other studies [10,18]. However, since the SURFACE database is only based on measurements done in three EU countries, the representativeness pavements across EU is low.

2.5. Road Lighting Design Comparison

The target of this study is to compare the road lighting performance of an installation designed using the CIE reference r-tables of a given road surface, with the performance of an installation designed using actual road surface data. The study is structured in four steps:

1. Selection of a CIE r-table among the CIE r-tables database;
2. Selection of different r-tables among the SURFACE r-tables database;
3. Selection of a road category and structural parameters;
4. Design of a road lighting system:
   Case A: With pole distance optimized for the selected CIE r-table;
   Case B: With pole distance optimized for each r-table.

2.5.1. Step 1

Selection of a CIE r-table to be used as reference r-table: the available CIE reference data for road surfaces are listed in Table 1. One set of data shall be selected to use as representative of standard available data of the most commonly used road surfaces in Europe. To identify it, the SURFACE consortium gathered information among stakeholders, project participants and road authorities. The collected information and road surface corresponding CIE characterization is shown in Table 1:

- In Switzerland, the most used table is R3. They sometimes measure Q_0 and then scale the R3 table;
- In Italy, C2 is used with $Q_0 = 0.07$ in roads and C2 with $Q_0 = 0.056$ in tunnels;
- In France R2 or R3 are generally used and there is no scaling according to Q_0;
- In England, C1 and C2 are used;
- In the Nordic countries, N2 is used with $Q_0 = 0.08$ or N1 with $Q_0 = 0.1$ Wet tables W2 or W3 are also used.

Table 1. CIE reference data of road surfaces for design calculations, type of road, countries of adoption as reference data for design calculation.

Table Family	Standard Table	Q_0	S_1	Country of Adoption
R	R1	0.1	0.25	
	R2	0.07	0.58	France
	R3	0.07	1.1	Switzerland, France
	R4	0.08	1.5	
N	N1	0.1	0.18	Nordic countries
	N2	0.07	0.41	Nordic countries with $Q_0 = 0.08$
	N3	0.07	0.88	
	N4	0.08	1.55	
C	C1	0.1	0.24	England
	C2	0.07	0.97	England, Italy ($Q_0 = 0.07$ in roads and 0.056 in tunnels)

In the end, the most used reference data for lighting design is the C2 road surface type because it is used in two different European countries and it also lies between R2 and R3 which are the tables used in two additional European countries.

2.5.2. Step 2

Selection of different *r*-tables among the SURFACE *r*-tables database: as stated above, SURFACE will provide to CEN and CIE not a single collection of measured data (because of confidentiality obligations toward the data provider) but a collection built on all database values. Therefore, in this study five different *r*-tables representing median and extreme values among the available *r*-tables have been selected. The values in Table 2 are representative of Q_0 and S_1 parameters of road surfaces used in design calculations in Step 4:

- very light and diffusive road surface behaviour, like for example cement or synthetic pavements,
- the median of the values representative of current bituminous roads,
- very specular road surface behaviour, like a specular bituminous pavement,
- very dark bituminous pavement.

Table 2. Relevant photometric characteristics of selected road surfaces.

Road Surface Type		Relevant Photometric Parameters	
Database	Description	Q_0	S_1
CIE	Reference C2	0.070	0.970
SURFACE	Very Bright	0.138	0.410
	Bituminous Diffuse	0.070	0.253
	Bituminous Median	0.059	0.730
	Specular	0.060	2.550
	Very Dark	0.037	0.560

Figure 3 shows Q_0 and S_1 values of CIE standard *r*-tables and the values of the selected road surfaces from the SURFACE database and Figure 4 shows the reflective behaviour in space (q values) of the selected road surfaces.
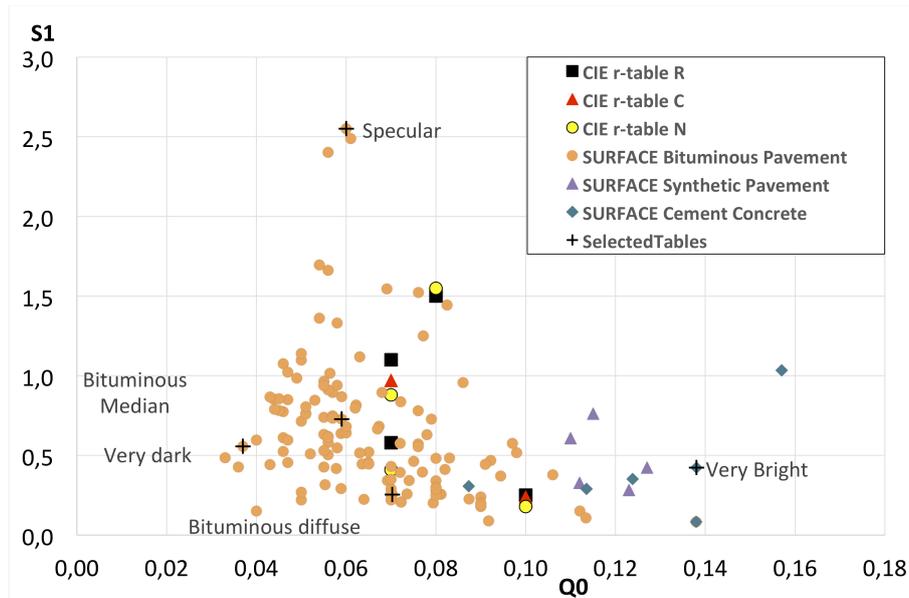
Figure 3. Q_0 and S_1 values of road surfaces in Table 2 and the current SURFACE database composed of 138 stabilised pavements.
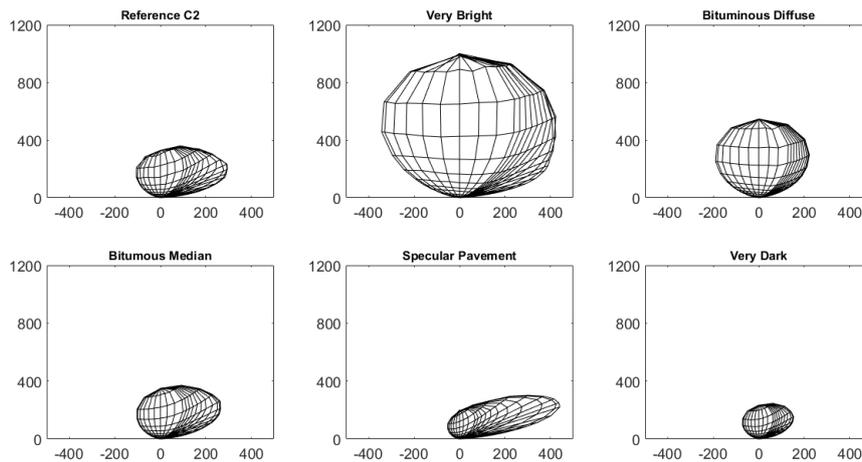

Figure 4. A 2D projection of *r*-table values of selected road surfaces of Table 2. The horizontal axis is $10^4 r \sin\gamma\cos\beta$, while the vertical axis is $10^4 r \cos\gamma$.

2.5.3. Step 3

Selection of a road category and structural parameters: in EN 13201-5 there are several calculations on energy savings for the M3 category with a given road dimension profile. In order to simplify data comparison and to provide useful data to CEN, the same road category and profile was chosen in this study. Table 3 shows the road dimension profile and normative requirements for the M3 category which is a road for motorized vehicles with high driving speed as in CEN TR 13201-1 [6]:

Table 3. Road dimension and normative lighting system requirements as in EN 13201-2.

Road Dimension Profile		Normative Requirements as in EN 13201-2			
Width [m]	No. of Lanes -	L [cd/m^2]	U_0 [-]	U_l [-]	f_{TI} [%]
7	2	>1	>0.4	>0.6	<15

L is the road surface luminance; U_0 is the overall luminance uniformity calculated as ratio of the lowest to the average luminance value; U_l is the longitudinal uniformity of luminance calculated as the ratio of the lowest to the highest road surface luminance in a line in the centre along the driving lane; f_{TI} is the threshold increment of an object in the road surface evaluated as the percentage of increased contrast to ensure object visibility in presence of glare generated by luminaires of the installation.

2.5.4. Step 4

Design of a road lighting system: road lighting designers usually face two different tasks:

- Design of a road lighting system using CIE reference table of the selected road (Table 2): the pole distance and luminaire set-up are optimized for C2 road surface. Then in the actual situation the road surface can be very different from the selected C2. Case A;
- Design of a brand-new system for a known actual road surface behavior (Table 2): the position of the poles and luminaire set-up are optimized for the given road surface behavior. Case B.

The design of a lighting system is based on an iterative process to optimize the installation parameters able to fulfill the normative requirements for the given road category. Every lighting fixture is already optimized for a specific condition of installation, e.g., installation on high or low poles, on the side or the centre of the road, on poles with or without arms, etc. In this study we chose a lighting fixture equipped with an LED source for installation on high poles on a single side of the road.

For both cases (A and B), the lighting system was designed for road category M3. Based on the input parameters, shown in Table 4, the software provides as output the optimized geometrical installation parameters (distance between poles, arm tilt, and arm length) which fulfill the normative requirements of Table 4 and the calculated photometric values of normative parameters. We have chosen to use Dialux 4.13 for our calculations because in this version of the software it is possible to import specific *r*-tables for the lighting design.

Table 4. Input parameters for lighting design for Case A and Case B.

Parameter	Value
Lighting class	M3
Luminous Intensity class	G3
Glare Index class	D.5
Pole height	10 m
Source height	9.87 m
Pole arrangement	single side
Pole road side distance	2 m
Luminous flux (light source)	13,245 lm
Luminous flux (luminaire)	12,185 lm
Luminous intensity (luminaire)	at 70°: 677 cd/klm
	at 80°: 27 cd/klm
	at 90°: 5.08 cd/klm

In case A, the optimization of installation parameters was made by optimizing the results for the C2 road surface and photometric parameters were then calculated for road surface types of Table 2 with the same fixed installation parameters (pole distance and luminaire alignment), so as to replicate the case of a lighting system designed for a CIE reference *r*-table but then the actual road surface is

different or later renewed. Case A optimized installation parameters are shown in Table 5. In case B the installation parameters are optimized for each road surface, as to simulate the case of a road lighting system designed purposely for each road surface actual photometric characteristics. The case B optimized installation parameters are shown in Table 6.

Table 5. Optimized pole distance and luminaire position for Case A.

Parameter	Value
Power of the luminaire	79 W
Pole distance	44 m
Luminaire tilt	5°
Arm length	2 m

Table 6. Optimized pole distance and luminaire position for Case B.

Road Surface Type	Power of the Luminaire [W]	Pole Distance [m]	Arm Length [m]	Luminaire Tilt
Reference C2	79	44	2	5°
Very Bright	59	45	1	0°
Bituminous Diffuse	79	44	1	0°
Bituminous Median	86	45	2	0°
Specular	79	36	1	5°
Very Dark	112	35	1	0°

3. Results

The software for road lighting system design provided the following results for the two aforementioned design options: Case A in Table 7 and Case B in Table 8.

Table 7. Road lighting design values for Case A.

Road Surface Type	L [cd/m²]	U_0 [-]	U_l [-]	f_{TI} [%]	E mean [lx]	Poles Per Kilometre [-]
Normative requirements	>1	>0.4	>0.6	<15	-	-
Reference C2	1.01	0.60	0.64	13	14	23
Very Bright	2.06	0.62	0.63	7	14	23
Bituminous Diffuse	1.05	0.71	0.52 *	13	14	23
Bituminous Median	0.91 *	0.62	0.64	14	14	23
Specular	0.96 *	0.38 *	0.32 *	14	14	23
Very Dark	0.57 *	0.69	0.67	20 *	14	23

* no normative fulfillment.

For the Case A only, also the percentage of differences between the actual road surface and the C2 road surface calculated values of L, U_0 and U_l of Table 7, are shown in Table 9. The difference was calculated as:

$$\Delta V = \frac{V_{test} - V_{C2}}{V_{C2}} \tag{7}$$

where:

V can be either L, U_0 or U_l quantity of C2 reference of the road surface under test.

Table 8. Road lighting designed values for Case B.

Road Surface Type	L [cd/m^2]	U_0 [-]	U_l [-]	f_{TI} [%]	E mean [lx]	Poles Per Kilometre [-]
Normative requirements	>1	>0.4	>0.6	<15	-	-
Reference C2	1.01	0.60	0.64	13	14	23
Very Bright	1.07	0.68	0.60	6	8	22
Bituminous Diffuse	1.06	0.72	0.60	14	15	23
Bituminous Median	1.00	0.61	0.60	15	16	22
Specular	1.04	0.43	0.60	13	17	28
Very Dark	1.00	0.67	0.61	6	31	29

Table 9. Differences between calculated values of the selected road type and reference C2 road.

Road Surface Type	$\Delta(L)$ [%]	$\Delta(U_0)$ [%]	$\Delta(U_l)$ [%]
Very Bright	104	3.3	−1.6
Bituminous Diffuse	4	18.3	−18.8
Bituminous Median	−9.9	3.3	0
Specular	−5	−36.7	−50
Very Dark	−43.6	15	4.7

Following the indication of EN 13201-5 [4], several energy performance indicators are calculated:

- D_P, power density indicator, ratio between the system power of the lighting installation over the mean illuminance on the reference area. Because in Case B the pole distance is optimized for the different road surfaces, reference area is weighted for the number of poles installed in 1 km of the road of Table 3.
- D_E, annual energy consumption indicator, as the energy consumption considering 4000 h as time in which lighting is provided, as in [4]. It is weighted for the number of poles installed in 1 km of the road of Table 3.

Because not all installations in Case A (fixed pole distance) fulfill the normative requirements for luminance in Table 3, the luminous flux of the luminaires was rescaled in order to reach the minimum normative luminance value of 1 cd/m^2. The results are shown in Table 10 and are used for performing calculation on energy performance indicators, comparison is shown in Table 11. The total system power, *P* was calculated for both indicators, neglecting the operational power of flux regulators (P_{ad}), and considering the simplified assumption of a linear proportionality between luminous flux and power consumption of each lighting point.

Table 10. Road lighting with rescaled values to fulfil the normative requirement on luminance for Case A.

Road Surface Type	Luminaire luminous Flux [lm]	Luminaire Power [W]	L [cd/m^2]	U_0 [-]	U_l [-]	f_{TI} [%]	E mean [lx]
Reference C2	12,064	78.2	1.00	0.60	0.64	13	13.9
Very Bright	5915	38.3	1.00	0.62	0.63	6	6.8
Bituminous Diffuse	11,605	75.2	1.00	0.71	0.52	13	13.3
Bituminous Median	13,390	86.8	1.00	0.62	0.64	14	15.4
Specular	12,693	82.3	1.00	0.38*	0.32	14	14.6
Very Dark	21,377	138.6	1.00	0.69	0.67	22	24.6

* no normative fulfillment.

Table 11. Energy performance indicators of road lighting of Case A calculated from the rescaled values of Table 10.

Road Surface Type	q_{inst}	Power Density Indicator D_P	Annual Energy Consumption Indicator D_E	Difference on D_E vs. C2
	[-]	[mW/lxm^2]	[Wh/m^2]	[%]
Reference C2	1.03	18	1016	-
Very Bright	2.1	18	498	−51
Bituminous Diffuse	1.07	18	977	−3.8
Bituminous Median	0.92	18	1127	11
Specular	0.98	18	1069	5.2
Very Dark	0.58	18	1800	77.2

For Case B, no compensation has been calculated because every lighting system fulfil the normative requirements. However, the reference area has been compensated for the number of poles per kilometre of road, e.g., for the very dark road surface, 26% more poles are needed per road kilometre. Power indicators are shown in Table 12.

Table 12. Energy performance indicators of road lighting of Case B calculated from values of Table 8 considering the actual power and of luminaires as described in Table 6.

Road Surface Type	q_{inst}	Power Density Indicator D_P	Annual Energy Consumption Indicator D_E	Difference on D_E vs. C2
	[-]	[mW/lxm^2]	[Wh/m^2]	[%]
Reference C2	1.03	18	1016	-
Very Bright	0.98	24	749	−27
Bituminous Diffuse	1.01	17	1026	0
Bituminous Median	1.06	17	1092	6.4
Specular	1.02	18	1254	22.2
Very Dark	0.87	15	1829	78.2

4. Discussion

Case A describes the case of a road lighting system designed and optimized for a C2 surface, and normative road lighting values (luminance and uniformity) for five additional road surface types are calculated and shown in Table 7. The results of Table 7 describe a common situation. when the road lighting design is performed considering a road surface behaviour described in a reference table (CIE *r*-tables) but the discrepancies between the photometric characteristics of the actual pavement and the reference pavement are not known, or a new/different pavement is installed during the life of the lighting system (that is some tens of years). Under these circumstances, some requirements of standard EN 13201 to ensure safety and visibility of road users, cannot be fulfilled. This is the reason it ends up that designers adopt heuristic overestimation of the system with great disadvantages from energy consumption point of view, towards the EU 2020 targets.

Case A results show that wrong evaluations can occur when the installed pavement differs from the selected CIE reference pavement: Table 9 shows a relevant underestimation (more than 40%) for a very dark road surface and an overestimation for a bright pavement (more than 100%). This occurs not only for luminance values, but uniformities are not fulfilled either, in particular for specular and very dark road surfaces. If the lighting system is equipped with a luminous flux controller (i.e., a smart lighting system), normative requirements can be fulfilled as shown in Table 10 for all

cases except for the requirements on uniformity for a specular surface. Using smart control, the energy consumption differences are evident (annual energy consumption in Table 11): relevant energy consumption advantages (51% savings Table 10) occur for the very bright surface, while a common road surfaces like the median bituminous pavement need more energy to fulfil the normative requirements (which, indeed, ensure road users safety). In case of very dark surfaces the energy consumption for ensuring the same safety is very high. These circumstances are also confirmed by the values of the q_{inst} parameter (Tabel 10): indeed q_{inst} is designed to acknowledge with high values the luminaires able to achieve the same road luminance with the lowest illuminance. In case A design, the same luminaire is used for all road surface types, but the luminous flux controller, introduced to fulfil the normative requirements, led to an illuminance reduction for bright surface as much as the relevant increase for very dark pavements (Table 10) rewarding again the energy savings of bright surfaces.

Case B results describe a simplified short-term impact of the SURFACE project: lighting system are designed and optimized for the actual installed road surfaces. To simplify calculations, results of Table 8 are calculated using the same LED fixture family considering only the simple optimizations of pole distance, lighting fixture tilt and pole arm length. This is the reason the energy consumption advantages of Case A calculations are not significantly different. A long-term impact of the project would be the design optimization of lighting fixtures to make the most of (finally known) reflective behaviors of road surfaces, with luminaire families optimized for specific Q_0 and S_1. Again, the impact of very dark surfaces from an energy consumption point of view is evident, but the knowledge of *r*-tables of the road surfaces ensures the fulfilment of all normative requirements for all tested road surfaces. The prerequisite of Case B to use the same luminaire family demonstrates the shortcomings of estimations based on the q_{inst} quantity when values of bright and dark surfaces are compared. This occurs because too much emphasis is put on illuminance as for the D_P quantity. A fully optimized design would require not only more iterations but a different choice of lighting fixture too.

The current approach to road lighting design does not take into account of ageing of pavements (from the photometric performance point of view). Moreover ISO and CIE recently published a standard [25] on maintenance factors involved in lighting, but only maintenance factors due to ageing of luminous sources/luminaires and indoor surfaces (with reference only to tunnel surfaces) are considered. Indeed, the SURFACE project is also investigating the influence of ageing on *q* values and several *r*-tables of aged surfaces are available, and as aforesaid are currently not included in the SURFACE database. These data are the starting point for future investigations on the relationship between ageing and photometric performance of road lighting that will include a relationship, currently neglected, between maintenances of luminaires, sources and pavements.

The results of both Case A and Case B show advantages in using very bright road surfaces: the fulfilment of safety parameters for road users (with excellent uniformities) with large energy savings. Actually from the results it seems that the largest energy saving would be when the system is designed for C2 road. The reason is that to simplify comparisons among different cases, the same lighting fixture was used. To increase optimization for Case B it is required to change lighting fixture family to fit better with the bright road behaviour. In the eventuality of a road surface replacement on an existing lit road, the advantages in using a brighter road surface are achieved if and only if, the lighting system would be equipped with controllers of luminaires luminous flux, to ensure compliance with standard requirements and energy savings. Similar results of using bright surfaces, with the additional advantages related to the mitigation of urban eating island, also emerged in the literature [26].

Bright road surfaces entail also an improvement in the safety of users not limited to M lighting class roads, but extended to C and P lighting classes because visual perception of objects (obstacles or pedestrians) on bright pavements is based on opposite contrast: objects are perceived against the light background of the carriages. In addition the luminous flux reduction required for M lighting class, together with the increase of the surrounding luminance due to diffuse reflection brings with

it a reduction of glare from the installed lighting sources (values of f_{TI} in Table 8 and Table 10) . Unfortunately, the counter effect is a possible increase of light pollution.

5. Conclusions

This research is part of the works of the SURFACE project and provides evidence of the need not only of the lighting community, but also of the EU for measurements and reference data of actual road surface photometric characteristics. SURFACE will provide the groundwork data (e.g.: metrological infrastructure, measurement methodologies, reference data, new geometries, reference materials for calibration, and portable measuring device) for a more efficient, more sustainable and safer road lighting design to be acknowledged in future standards for the benefit of all EU night-time road users. Road lighting consumption is about 6-7% of the total country electrical consumption, but for municipalities may be as high as 50% of the entire electrical consumption [27]. More efficient lighting design based on SSL and Smart Lighting not limited to roads of M lighting class but also extended to P and C lighting classes can bring energy savings up to 70% for M lighting class roads, lowering the CO2 impact, and allow the development of smart cities. This research quantifies the discrepancies in terms of energy consumption and road users safety when using the current reference data instead of data of the actual road surface installed and the advantages of smart system for lighting control.

Abbreviations

The following abbreviations are used in this manuscript:

CEN	European Standard Organization
CIE	Commission International de l'Eclairage
EMPIR	European Metrology Programme for Innovation and Research
EURAMET	European Association of National Metrology Institutes
EU	European Community
LED	Light Emitting Diode
NMI	National Metrology Institute
SSL	Solid-State Lighting
UNI	Ente Italiano Normazione

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