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RMG: -		

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TABLE OF CONTENTS

1. Overview

The knowledge of the so-called luminance coefficient *q* (ratio between the luminance of the road surface and the illuminance on it for given directions of illumination and observation) is an unavoidable requirement for designing road lighting installations to ensure adequate road luminance is adequate and visibility for road users and traffic safety, as well as, lowering energy consumptions in accordance with current EN standards. The project results have provided the necessary groundwork for a metrological infrastructure and supported the European standardisation process by developing validated, optimised and reliable geometrical conditions for instrument calibration, along with reference data that is representative of current road pavements. Thus, ensuring more efficient, sustainable and safer road lighting design. In addition, SURFACE completed a full evaluation of the energetic impact of current road lighting design procedures based on reference outdated r-tables. The optimized measurement geometries outlined by the project addressed the needs of different road user (e.g. drivers, cyclists and pedestrians) while taking into account their viewing distance, actual traffic conditions, velocity and road environment. In terms of traffic safety, the project established new observation angles, homogeneous with actual users' viewing conditions, leading to road lighting systems with visually improved safety performances. Key project outputs such as an initial version of a portable instrument for road marking characterization, the developed RM and CRM, and the uncertainty evaluation software (Lumcorun), will push forward the market for developing new and adequate laboratory and portable measuring instruments for the characterisation of road surface, as requested in EN 13201 standard series As such, normative technical committees (TCs), lighting designers and road authorities now have access to reliable luminance coefficient data describing the behaviour of contemporary road surfaces.

2. Need

Across Europe about 40 % of the 5.5 million kilometres of roads have lighting. Current EU standards on road lighting (i.e. EN 13201 series) seek to establish road luminance values able to satisfy quantitative and qualitative performances in terms of safety, visual appearance, and energy consumption. Thus, the weighting and spacing of a road lighting system (i.e. luminous flux installed per kilometre) are calculated accordingly, to comply with the suggested luminance values of the assigned road class that warrant the visibility for road users' safety. Usually, the design of such lighting systems (e.g. the definition of the installation layout, luminous intensity, distribution of luminaires, and luminous flux installed per kilometre or power density indicator) considers reference weighted *q* data (*r*-tables) of the road surface. In the EN 13201 Road lighting Standard series, *r*-tables provide values only for the necessary incident and view directions for traditional lighting installation (i.e. installation luminaires height greater than 10 m and columns inter-distance of about 30 m) and the *q* data, representative of the road surface behaviour, for those directions are missing. Road lighting designers adopt as de facto, standard values, the *r*-table or the equivalent *q* values published in CIE documents. However, these data are based on measurements performed on concrete samples more than 40 years ago without traceability and uncertainty evaluation.

Recent studies have shown that the use of CIE data as reference, leads to large errors (on average over 30 %, but up to 50 % in worst case) on expected road luminance. Moreover, the photometric properties of road materials have changed over time due to new material components and laying techniques as well as the road lighting systems (i.e. LED sources, adaptive systems and smart lighting systems, and luminaires installed at lower heights). Such an evolving situation requires the definition of new values of *q* and an upgrade of the reference directions for its measurement. To ensure EU targets on Energy Saving and Road Safety are met, the project focussed on improving *q* reference data and reference geometries through a large metrological research review of basic concepts and metrological capabilities. After the 1st CIE international symposium on Road Surface Photometric characteristics (Torino, 2008), the revision of CIE TR 144 was set up in 2009, however no significative advances were made due to the lack of focused research, NMI involvement, and of collaborative approach within all involved figures. Owing to the project's achievements, CIE TC4-50 is finally able to attain its task. A new CIE TR144 has been planned in for the next years and will based on the SURFACE pre-normative guidelines and results.

3. Objectives

The goal of this project was to address the current deficiencies in European Standards regarding (i) the definition and characterisation of the road surface photometry, (ii) traceable measurement and characterisation methods for road surface characteristics and (iii) traceable reference data for photometric tables useful in the design process of road lighting installations. The project results will be used by CEN TC169/WG12 in the next revision of EN 13201 series, and by CIE TC4-50 in the revision of pertinent CIE publications. The specific objectives were:

1. To develop optimised measurement geometries for the characterisation of photometric quantities for road surface materials to support EN 13201 'Road Lighting' and its future revisions.
2. To produce technical and metrological specifications for instruments used to measure luminance and reduced luminance coefficients of road surfaces in laboratories or on-site, including methodologies for calibration, establishing traceability and evaluating the measurement uncertainty.
3. To develop pre-normative guidelines for measurement methods and procedures, for the future evolution of European standards to include aspects such as mesopic visual conditions (CIE191:2010), reduced obtrusive light and reduced light pollution of road lighting installations.
4. To develop pre-normative guidelines for photometric characterisation of road and pavement surfaces, including factors such as aging of road surfaces, wet conditions, spectral properties, diffusion of adaptive lighting systems (smart lighting), luminaire luminous intensity distribution and effects of measurement uncertainty in tolerance calculations.
5. To contribute to the standards development works of the technical committees CEN TC169/WG12 and CIE TC4-50 through the provision of data, methods, guidelines and recommendations. In particular traceable data related to new geometries and materials for inclusion in updated photometric tables of pavements in the international CIE database shall be provided. To ensure that the outputs of the project are aligned with their needs, results will be communicated quickly to those developing the standards and to those who will use them (e.g. lighting engineers, road designers), and in a form that can be incorporated into the standards at the earliest opportunity.

4. Results

In this section the project's technical outputs are presented against each of the objectives, on an objective by objective basis.

4.1 Optimised measurement geometries for the characterisation of photometric quantities for road surface (Objective 1)

4.1.1 State of the art

Specifications concerning road lighting and photometry of road surfaces were established in the 1970s[1] Road lighting design and road marking visibility were developed primarily for drivers of motorised vehicles. The observation distances defined by standards correspond to inter-urban applications; however, these areas are rarely lit in Europe.

Road luminance is defined in the EN 13201-series of European standards[2][3][4][5] as the key parameter which road lighting has to fulfil in order to provide lighting intended to assure the safety of road users after dark. Road surface luminances, which allow the perception of possible obstacles and of the environment, are based on a vision model[6] and then realized through artificial road lighting.

The design of a road lighting system includes determination of the optimal combination of lamp power, height, spacing and luminaire optics to provide the desired road surface luminance. A road class is assigned according to road and traffic characteristics, following national requirements based on CEN/TR 13201-1:2014[6]

Road surface luminance is the light quantity perceived by drivers. It is directly related to the luminous intensity emitted by a luminaire in a given direction and the reflective characteristics of the road surface in the same direction, towards the viewing direction of the observer.

The luminance coefficient describes the geometric reflective behaviour of any material and in addition to road lighting design has applications including the creation of photo-realistic images, energy and lighting calculations. Since the lighting design can be done either before or after the road construction, road lighting calculations are usually performed using tabulated values of q for different road pavements, defined as reference pavements. EN standards also require on-site verification for compliance with national road lighting requirements. In this case, knowledge of the road pavement luminance values used in the design and the actual installed luminaire data are necessary. However, in practice the photometric characteristics of the pavements are not generally measured.

The method for characterising pavements photometrically was developed in the nineteen-seventies and updated in 1982 and 2001 [7] The quantities used in road lighting characterisation are described in three reports from the International Commission on Illumination (CIE)[8][9][10].

The surface of a pavement is classified according to its reflection properties. The most characteristic parameter is the luminance coefficient *q*, is the ratio between the luminance *L* in cd/m², which the observer sees, and the illuminance *E* in lux which is incident on the surface (Equation 1).

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

Since the nineteen eighties, for practical reasons the luminance coefficient was replaced by the reduced luminance coefficient *r* in cd/m²/lux, which is derived from *q* (Equation 2).

$$r = q\cos^3\varepsilon \qquad (2)$$

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 *ε* (see Figure 1).

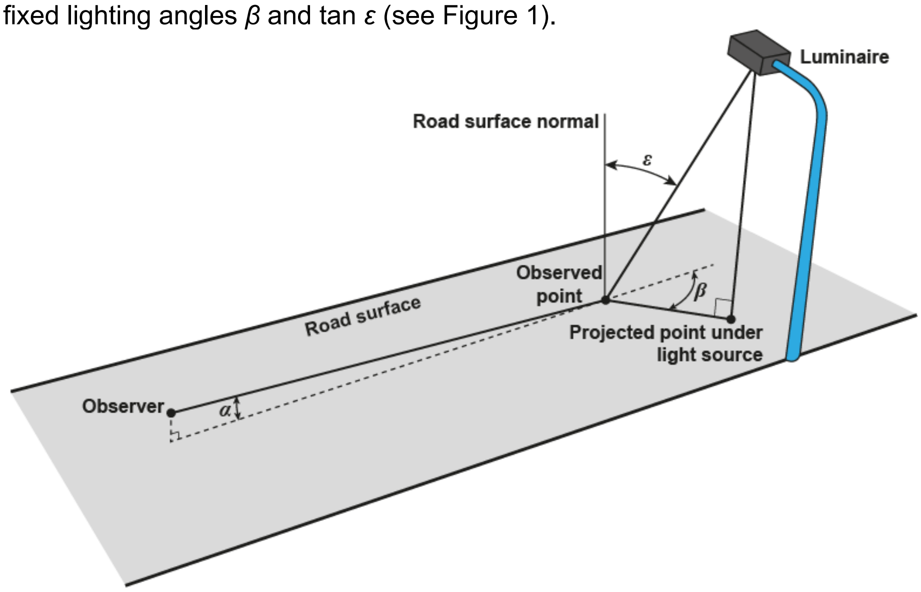


Figure 1. The photometric characteristics of the road surface depend on the angles of observation α, deviation β and incidence ε. By convention, according to CIE 066 and CIE 144, guidelines and road lighting standards, for the characterisation of road photometry α is set at 1°.

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 (Equation 3).

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

In practice, due to the finite number of measurements, the integration results in a numerical summation approximated with weighting factors corresponding to the solid angle attributed to each value $\Delta\omega$ and given for each combination of tan ε and β angles (Equation 4).[12]

$$Q_0 = \frac{\sum q \cdot \Delta\omega}{\sum \Delta\omega} \qquad (4)$$

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 (Equation 5).

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

Standard reflection tables are used worldwide, these based on measurements carried out in northern Europe in the nineteen-sixties and seventies [8]. However, discrepancies have been found in more recent measurements [11] [12] [13] [14]. These discrepancies are attributed to the change in pavement surface technology and aging of the road surfaces.

Since the geometries and quantities involved are very peculiar, partners (INRIM, CEREMA, RISE, AALTO, LNE and METAS) made a great effort to summarize and simplify descriptions and definitions and finally a complete overview of quantities and parameters for road surface photometric characterization is available. This provide great impact toward CIE TC4-50 and CEN TC169 for their future document revision.

The luminance coefficient depends of the nature of the road surface material and on the positions of the light source and the observer relative to the element under consideration, as defined by the fixed angles α, and combination of the lighting angles β and ε, see Figure 1. A reduced coefficient table called *r*-table was defined, where the luminance coefficient *r* is given for a combination of fixed lighting angles *β* between 0 and 180° and tan *ε* between 0 and 12. The luminance coefficient indicatrix also called reflexion indicatrix is a graphical representation of the *r*-table, which can be represented as De Boer 1967 (see Figure 2), or projected in 2D (see Figure 3).

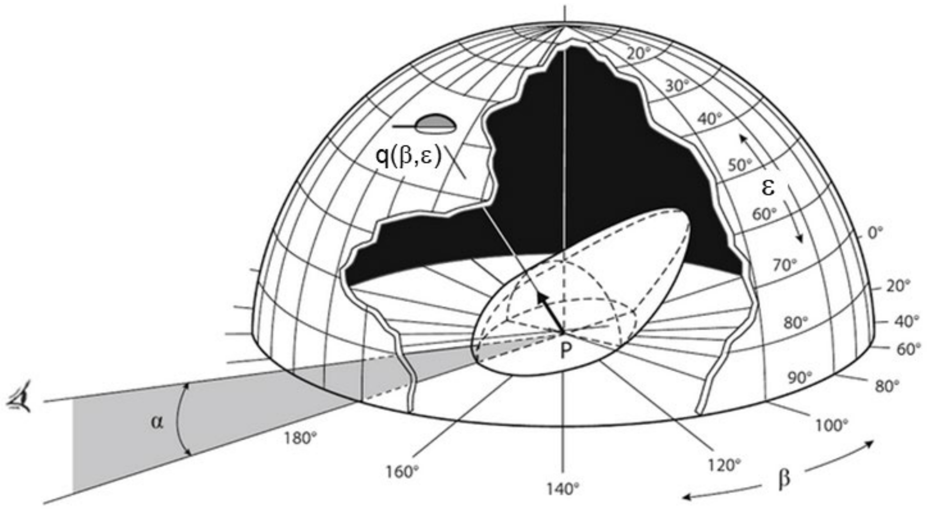


Figure 2: Luminance coefficient indicatrix, represented by De Boer in 1967

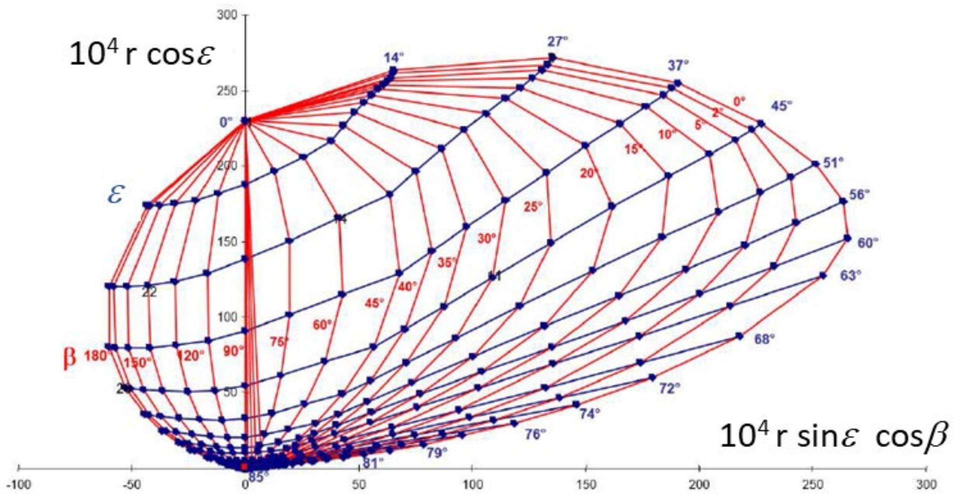


Figure 3: Projection in 2D of the reflexion indicatrix

The average luminance coefficient Q_0, represents the degree of lightness of the measured surface[15]. It is computed as the average of the luminance coefficients over the specified solid angle, Ω_0:

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

In the past 40 years, pavements have changed, driver visual conditions have changed, and traffic behaviour has changed. As a consequence, current road lighting systems are designed using data of road pavement characteristics which may not be representative of actual road surfaces [11] [12] [13] [14].. Road surfaces and luminaires have evolved over time. Awareness of the importance of measurement uncertainty and its relationship with industrial tolerances has also increased. Some studies show that the currently available CIE data may lead to errors on average luminance often over 30 % and sometimes over 50 % [14][16].

The geometry currently used with an observation angle of 1° for the design of pavement lighting was defined in the nineteen-seventies and confirmed in 1976 [8], 2001 [9],and 2019 [10]. In these CIE documents and in the road lighting standard EN 13201-3, the height of the eye of the observer is set at the nominal value of 1.5 m. In the same standard, the range of observation angle is conventionally assumed to be 1.0±0.5° according to a viewing distance between 60 and 160 m.

Concerning the characterization of road markings, other geometries are defined in the standard EN 1436 [17]. The eye of the observer is set at the nominal value of 1.2 m and the angle of observation is 2.29°, which corresponds to a distance of observation of 30 m. In the road marking standard, the tolerance on the observation angle is ±0.05°.

4.1.2 Optimised measurement geometries

With regard to illumination angles, there is a need for more data at grazing angles due to the use of guide lighting devices mounted at low heights, especially in tunnels. Since the r-table is only defined up to tan ε =12, when the mounting height of the luminaires is very low (H < 2 m), an extension for tan ε is needed. For this reason, in EN13201-3 the informative annex B defines an extended r-table format for luminaires with low mounting height. The r-table is extended in tan ε up to 20, by increment of 0.5 for every β angle. However, there is still a need for such data and a new calculation of Q0 should be proposed to take this table into account. However, up to know, it seems that nobody is able to make measurements at such grazing angles.

Concerning the observation angle, it is affected by both the vehicle type and the distance of observation. For drivers of motorized vehicles, in the EN13201 standards, the main lighting criteria for interurban driving are based on the road surface luminance and include the average luminance, the overall uniformity and the longitudinal uniformity. The driver's eye is assumed to be at 1.5 m above the road surface and the angle of observation is fixed to 1° below the horizontal, corresponding to a distance of 86 m ahead of the observer. This geometry is well adapted for a speed of 90 km/h, on motorways for example. However, nowadays, except in tunnels, there are few interurban lighted roads in Europe. Illuminated areas are located in urban environments where there are several types of road users (vehicle drivers, but also cyclists and pedestrians), travelling at different speeds. To define new observation angles, a first approach is to consider the stopping distance, which is a summation of the reaction distance and braking distance. Thanks to strong contacts of partners (INRIM, CEREMA, RISE and METAS) with road authorities and normative bodies, typical stopping distances are presented in the following table. For road safety, good visibility of obstacles within the stopping distance is very important.

Table 1 Stopping distance at different driving speeds in some EU countries and Switzerland

		Stopping distance on dry pavement in official documents (m)			
	Speed (km/h)	**France**	**Italy**	**Sweden**	**Switzerland**
Urban driving	**30**	13	22	16	16 - 22
	50	28	55	38	34 - 48
Interurban driving	**90**	70	136	121	88 - 115
	120	112	235	222	144 - 189

Concerning the height of the observer, the SURFACE proposal is to keep the height of the observer at the nominal value of 1.5 m, in order to be consistent with EN 13201 and the CIE recommendation. This height is adequate for drivers, cyclists, and pedestrians. In Table 2, the corresponding distance is computed for different observation angles. There is no impact for existing road surface and marking measuring devices because they consider a measuring angle, not a height, expressed as a nominal value.

Table 2. Distances which correspond to different nominal observation angles at 1.5-m height of observer.

Observation angle α (°)	1	2.29	3	5	7	10	20	45
Corresponding viewing distance (m)	85.9	37.5	28.6	17.1	12.2	8.5	4.1	1.5

The SURFACE consortium partners most involved in CIE activities and standardization bodies (INRIM, CEREMA, RISE and METAS) proposed to the whole consortium the approach of providing new observation angles suitable to the different road users. The SURFACE consortium, after discussion with the stakeholder community, recommends in Table 3 different nominal observation angles for different driving conditions and road users: for urban environment 2.29° (consistent with road marking standards and stopping distances in urban environment), for extra-urban environment 1° (consistent with previous geometries). The angle of 5°, corresponding to a viewing distance of 17 m, is an interesting complement, suitable for urban driving at low speed, cycling and for scooters. The angles of 10° and 20° are submitted to CIE TC4-50 for consideration as condition for describing the boundary between diffuse and specular behaviour.

Table 3. SURFACE recommendation for new geometries.

Road environment condition	**Nominal observation angle recommendation**
Extra-urban road	1°, viewing distance of 85.9 m
Urban road	2.29°, viewing distance of 37.5 m

SURFACE project has been able, during its duration, to produce an extensive international review on road photometry, including measurement devices, available data base, measurement methods, national choices of reference values for lighting design and energetic impact [14] but not only. SURFACE investigated also current geometries for road surface characterization and road-users' conditions of viewing and is able to suggest to international normative bodies (CEN and CIE) these findings and new approaches.

Regarding geometries the first evidence is about the most critical point of the current approach: the reference observation angle currently used in standard. The difficulties of doing measurements at 1° observation angle were already recognized in literature, but SURFACE not only highlighted and substantiated these issues but also proposed solutions. The large literature review and investigation among the SURFACE consortium and stakeholders whose results are summarized in this report bring SURFACE to suggest to reference normative bodies (CIE and CEN) the use of different geometries according the actual road environment, branching out several possible observation angles to be included at the earliest review stage of CIE 144 and EN 13201 documents.

4.1.3 Impact of new geometries

The above new geometries for road surface characterization needs to be implemented in lighting design programs and simulation tools, too. Some measurement devices for road luminance coefficient evaluation, can be easily adapted to the new angles of observation and other are going to be introduced in the market (two of them have been developed inside the SURFACE consortium), SURFACE promptly remind CIE TC4-50 and CEN TC169/WG 12 t that the same geometries have to be used also in lighting design and on-site verification too: the coherence between viewing conditions in road characterization (and reference tables), in lighting design and in on-site verifications, need to be assured at all levels.

Furthermore, these new geometries, allow the development of less expensive measurement devices and an increased accuracy also for on-site verification: geometrical constraints of 1° of observation entail difficulties in set up, increase influence of discrepancies in alignments and of lighting – viewing area, as well for on-site verification, the identification of measurement grid points and associated luminance values.

Additional impacts are expected also on luminance levels required for the different road lighting class: the current reference values are based on the results of visual experiments, carried out in the past century more than 60 years ago, on contrast threshold at 1° of observation angle on pavements and lit road of that period.

The definition of new angles of observation would have an impact on the required threshold luminance levels of uniformity. New subjective experiments are needed in order to define new reference values of contrast threshold to acknowledge not only the new SURFACE proposed geometries, but also current pavements, including the bright ones, LED sources, 3D objects detection (instead of 2D shapes as used in the past researches and tests), and the concept of moving observer. Unfortunately, because the coronavirus pandemic situation it was not possible to do the subjective tests using the virtual driving simulator of OPTIS-ANSYS to test visibility performances impact of new geometries. Instead of subjective experiment, the man effort and collaboration among CEREMA, INRIM and OPTIS-ANSYS was redirected toward multiple simulations of the new geometries and actual lighting performances of current road surfaces.

4.1.4 Summary of key research outputs and conclusions

This objective has been fully met since the project's approach towards observation angles satisfied the actual viewing conditions of road users. Thereby ensuring improving road safety of all users (e.g. drivers, cyclists and pedestrians). Going beyond the project's lifetime, two different proposals (10° and 20°) are under consideration for defining a viewing condition that can describe the boundary diffusing-specular behaviour which will be useful for applications like Smart Lighting with luminance camera in high position.

4.2 Pre-normative guidelines (Objective 3)

4.2.1 Pre-normative guidelines for measurement methods and procedures, for the future evolution of European standards

SURFACE activities were integrated with the CIE TC4-50 working plan, in particular pre-normative guidelines (namely deliverables called D5 and D6) were put in a form to be incorporated directly into the new revision of CIE TR144. For this reason, SURFACE consortium chose to keep guidelines confidential in order to ensure the direct incorporation into CIE TR144. The consortium NMIs (INRIM; METAS, RISE, AALTO, METROSERT) and CEREMA strongly collaborated in the definition of the guideline's contents. The pandemic situation cancelled all in person meeting and forced to virtual meetings that brough the additional value of more collaboration especially for document writing and revision. The consortium had a large number of weekly online meeting to produce the guidelines, a task that was possible to achieve only thanks to a strong collaborative effort. The following tables resume all SURFACE suggestions based on all findings of the project and proposed to CIE TC4-50 in a form to be directly incorporated into CIE TR144 next revision:

TOPIC	SURFACE Suggestions
Geometries of measurement – angle of observation	Extra-urban road: 1°, viewing distance of 85.9 m Urban road: 2.29°, viewing distance of 37.5 m Urban driving at low speed: 5°, viewing distance of 17 m, suitable for cycling and scooters Boundary between diffuse and specular behaviour: 10° and 20° are under consideration
Metrological requirement for instruments for *r*-tables	A measurement geometry that corresponds to the norm (observation angle) [1°, 2.29°] A measure that is representative of the surface (i.e. an average over enough points) [100 cm^2] Good collimation, i.e. small angular subtense of the light source [<0.2°] Small detector angular subtense, i.e. good telecentricity of the detector [<0.08° cf CIE 66-1984]
Uncertainty evaluation	Good calibration of the different elements Determination of the values of the relevant parameters contributing to the uncertainty

	Use of LUMCORUN software
Laboratory measurement procedure	
Sample identification and extraction	Reference the position of the extraction Avoid evident heterogenous area Clean the sample on-site Identify the circulation direction with a mark Additional suggestions in the confidential guidelines
Transport and storage	Place samples in conditions to maintain state Cover with protective material during transport Store samples indoors Additional suggestions in the confidential guidelines
Alignment	Ensure that the positioning of the source, sample and detector are correct with regards to each other The centre of the sample is the centre of the measurement Place the surface of the sample in the reference plane, corresponding to the measured plane
Recording	Sample: identification code and date of extraction, condition of storage, washing actions Laboratory: environmental conditions, any other relevant conditions including lamp control. Measuring device: time of switch-on of the device (including lamp) and time of start and end of measurement, and if used, reference material used for initial setup Additional suggestions in the confidential guidelines
On site measurement procedure	
Road	A figure shows all necessary information to be recorded about the measurement site and the road Road must be not used by vehicles at the time of measurement Environmental conditions: outside temperature above +5 °C, avoid fog
Selection of the measurement area	Chose a planar area without defects, use the suggested confidential contour gauge to identify convexities Pavement must be dry, unsalted Measurement shall be done in the direction of circulation Additional suggestions in the confidential guidelines
Sampling	Sampling: on each lane of circulation, in the centre and in the tyre tracks. Choose several sampling areas and perform at least 6 measurements,. Additional suggestions in the confidential guidelines
Recording	Place and conditions of measurement: type of road and its use, traffic, date, meteorological conditions, environmental conditions Type of pavement and all available information Pictures the pavement

	Additional suggestions in the confidential guidelines
Data analysis	
Measured data and statistics	Measured values depend on: heterogeneity of the surface, type of asphalt and binder, traffic, usage, ageing, the measured place additional confidential suggestions in the guidelines Avoid a mean value of the *r*-table, because it may not be representative of a physical surface Data to provide: most representative *r*-tables and the extremes additional confidential suggestions in the guidelines Devices measuring only Q_0 and S_1, provide the mean value and standard deviation Possible statistical approaches described in the additional suggestions in the confidential guidelines
Impact of additional pavement conditions	Additional influences: Time, traffic: the centre track is slightly darker and less specular than the tyre track Difficult to isolate the effect of traffic from the time and ambient conditions Studies show that Q_0 and S_1 are bigger in the circulated part of the road With salt or dust, the specularity is generally lower
Spectral properties	
Influence of the sources vs spectral reflectance of pavements	The design of a lighting system with RGB LED, low-pressure Sodium, high-pressure Sodium, and Xenon Pulsed is statistically more affected by the spectral behaviour of road surfaces The design of a lighting system equipped with LED sources, especially neutral LED (i.e. blue LED and phosphor) leads to low discrepancies (in the range −1 % to +2 %, which is half compared to the aforementioned sources)

4.2.2 Summary of key research outputs and conclusions

SURFACE engaged with relevant standardisation organisations, in particular with CIE to disseminate and raise awareness of key project outputs such as: new reference data for q of actual road surface, the evaluation of the impact of their usage, new geometries, a detailed investigation on instruments performances for on-site and laboratory evaluation of photometric road surface characteristics, a reference test set to compare lighting performances of systems and road surfaces, and two detailed practical guidelines for direct implementation in the standard. All of these project results will provide the basis for the new revision of CIE TR144 and EN lighting standards. This objective has been met.

4.3 Technical and metrological specifications for instruments used to measure luminance and reduced luminance coefficients of road surfaces (Objective 2)

Table 4. An overview of European Laboratory instruments found in the literature.

Characteristic	Laboratory or group								
	METAS (LaFOR)	Cerema	Univ. Gustave-Eiffel	INRIM	Univ. of Padova	Aalto Univ.	Technische Univ. Dresden	RISE	Lappeenranta Univ. of Tech.
Location	CH	FR	FR	IT	IT	FI	GE	SE	FI
Automation	Partial	Full	Full	Full	Full	Full	INA	Partial	None
L/*E* meas. procedure	Absolute	Absolute	Relative	Relative	Relative	Relative	INA	Absolute	Absolute
Source angular subtense	0.5°	10°	INA	0.1°	0.1°	<3°	INA	1.4°	0.4°
Detector angular subtense	1.1°	0.3°	0.3°	0.1°	0.1°	<0.2°	INA	0.25° to 1.0°	1°
Observation angle α	0.6° to 1.4°	1° 2.29° 5° 10° 20° 45°	1° to 90°	0° to 90°	0° to 90°	1°	1° 3°	1.0° to 80°	1°
r-table	Yes	Yes	Yes	Yes	Yes	Yes	Yes	IP	XP
Q_0	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
S_1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	XP
Meas. field size (mm²)	≥ 10^4	≥ 10^4	7540	7850	> 10^4	1960	INA	< 10^4	3850

Note:
INA = Information not available
IP = Interpolation
XP = Extrapolation

Table 5. An overview of European portable devices found in the literature.

Characteristic	**Laboratory or group**							
	METAS	**METAS**	**Cerema**	**Cerema**	**Univ. of Padova**	**Minel Schreuder**	**Rtech Schreuder**	**NMF**
Name	MoFOR	LTL-200	COLU-ROUTE	COLU-ROUTE2	-	Memphis	Memphis	NMF box
Location	CH	CH	FR	FR	IT	RS	BE	DK
Illumination	Complete source scan	Restricted measurement geometry combinations						
		8 sources	27 sources	27 source	6 sources with β rotation	4 sources	4 sources	2 sources
Source angular subtense	9.5°	1.1°	5.2°	3.2°	INA	INA	INA	20° 4°
Detector angular subtense	0.7°	1.1°	8.6° × 0.9°	INA	INA	INA	INA	1.2°
Observation angle α	1°	1°	1°	1°, 2.29°, 3°, 5°,10°	1°	5°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80° for β=0°, 10°, 20°, 30°, 150°		1° 1.5° 2.29°
***r*-table**	Yes	No	IP & XP	IP & XP	IP & XP	IP & XP	Search of the closest table in a data-base	No
Q_0	Yes	Linear combi-nation	Yes	Yes	Yes	Yes		Linear combination
S_1	Yes	Yes	Yes	Yes	Yes	IP		Yes

Meas. field size (mm²)	7850	5600	2000	2000	~8000	7850	7850	8000
Specific charac-teristics	No	No	No	No	No	Inverse light path	Inverse light path	Meas. Q_d

Note:
INA = Information not available
IP = Interpolation
XP = Extrapolation

4.3.2 Usage of ILMD for on-site measurements

ILMD devices are mainly used to measure luminance, but because the relationship between luminance and illuminance by the luminance coefficient q, with a deep knowledge of q (BRDF) of the material, it is possible to evaluate the illuminance on the surface too. Most applications need absolute values of the related photometric (luminance absolute units calibration) or radiometric quantities, but thanks to device peculiarities like linearity and high reproducibility, ILMD can be used also as relative measurement device: keeping the device setting (geometrical settings like focus and aperture) similar and varying only the exposure time, luminance ratio differences are related to exposure time and reading values with no need of absolute calibration in cd/m2.

An ILMD can be used as simple luminance meter to measure r-tables or as a device for onsite evaluation of r-tables as suggested by several studies [30]–[33]. The capability of ILMD to resolve different direction of observations by the different pixels are the key performance for road surface measurement applications. The idea is to use the installed road lighting luminaires as illuminating source to measure on site the reflectance characteristics of the road surface and was first proposed in 2008 [30] . By definition, the reflexion table is a matrix with a double entry which established the relation between luminance coming from a point of the roadway and the luminous intensity aiming to that point, resulting from a light source, for a given observation angle. The formula below expresses this relation:

$$L_P = r(\tan \gamma_P\, ,\, \beta_P).\frac{I_P}{h^2}$$

Where Lp is the luminance coming from a small area of the road surface, Ip the incidental light intensity on this area and h the mounting height of the light, as in Figure 4.

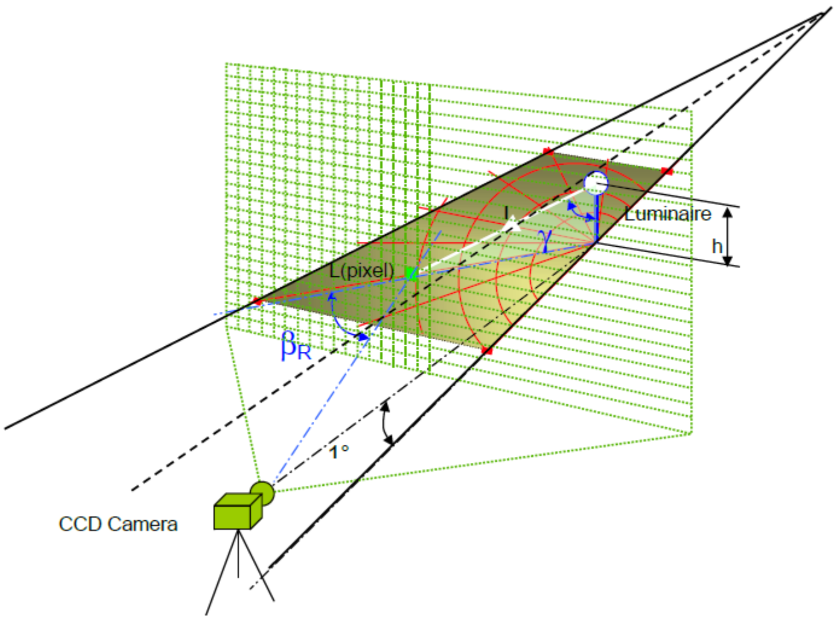


Figure 4: Schematic representation of the catch of a luminance measurement in road lighting by a digital luminancemeter[30]. A small area of the roadway corresponds to a pixel on the ILMD. Knowing the coordinates of this area as well as the intensity and direction of the light beam, the corresponding r coefficient could be calculated for the determined γ and β angles.

4.3.3 Measurement procedures

Since the luminance coefficient is a ratio of two quantities (luminance and illuminance), there are basically two measurement approaches: the absolute method and the relative method.

Absolute method: the definition of the luminance coefficient is directly applied. Thus, the luminance coefficient of a test surface $q_{\mathrm{T}} = \frac{L}{E}$ is calculated as the ratio of the two quantities each one measured with a given detector calibrated in absolute units (for luminance and for illuminance) with its own uncertainty.

In terms of measured signals

$$q_{\mathrm{T}} = \frac{s_{\mathrm{L,T}} - s_{\mathrm{L0,T}}}{s_{\mathrm{E,T}} - s_{\mathrm{E0,T}}} \cdot \frac{k_{\mathrm{L}}}{k_{\mathrm{E}}}, \qquad (1)$$

Where: $s_{\mathrm{L,T}}$ is the signal measured by the luminance detector when measuring the test surface, $s_{\mathrm{E,T}}$, the signal of the illuminance detector,($s_{\mathrm{L0,T}}$, $s_{\mathrm{E0,T}}$ respectively their dark signals) k_{L} the calibration factor of the luminance detector, u(k_L) its calibration uncertainty, and k_{E}, the calibration factor of the illuminance detector, u(k_E) its calibration uncertainty .

It can be noted here, that the illuminance can be measured once, for the normal incidence, and then deduced for other incidences applying the cos (γ) law and optionally monitoring the light source.

This method involves two different calibration uncertainties u(k_L) and u(k_E) that should be conveniently included in the evaluation of the luminance and illuminance in the given geometry of measurement of q_T values.

Relative method: a Reference Material (RM) is used to calibrate the system, so that only one detector not calibrated in absolute luminance units (cd/m^2 or lx) is used. This approach has the advantage of involving only the uncertainty on the reference standard calibration but requests a deep investigation on the metrological performances of the detector including linearity. In addition, often an additional detector is used to monitor the signal of the source, to take into account of possible source emission deviations:

$$q_{\mathrm{T}} = q_{\mathrm{R}} \frac{s_{\mathrm{L,T}}}{s_{\mathrm{L,R}}} \cdot \frac{s_{\mathrm{M,R}}}{s_{\mathrm{M,T}}} , \qquad (2)$$

where $s_{\mathrm{L,T}}$ is the signal of the detector when measuring the test surface, $s_{\mathrm{L,R}}$ is the signal of the detector when measuring the reference surface, $s_{\mathrm{M,R}}$ is the signal of the monitor detector of the source when measuring the reference surface, $s_{\mathrm{M,T}}$ is the signal of the monitor detector of the source when measuring the test surface and q_{R} is the luminance coefficient of the reference surface, u(q_R) its calibration uncertainty.

This method involves only one calibration uncertainty u(q_R) with a dependence on the geometry of measurement that should be conveniently included in the evaluation of q_T.

The strict definition of the luminance coefficients (and of the BRDF) implies that the illuminance is measured at a given point (i.e. within an infinitesimal small area) and the luminance at the same point, in a given direction (i.e. within an infinitesimal small solid angle). In addition, the incident light should originate from a given direction (i.e. a source with infinitesimal solid angle). In practice, this is not possible as finite apertures are necessary to emit and collect light. Furthermore, road surfaces are highly non-uniform, hence the luminance coefficient will vary at each point and averages over a certain surface area need to be taken

The direct application of the definition of luminance coefficient implies that luminance is measured with a luminance meter, an imaging luminance measurement device (ILMD), or a similar setup which limits the field-of-view of the detector. In this configuration, the illuminated surface is usually larger than the measurement surface. The limitation of the field of view can also be made by limiting the illumination field. In this configuration, the illuminated field is smaller than the actual field-of-view of the detector. Both cases are shown in Figure 5

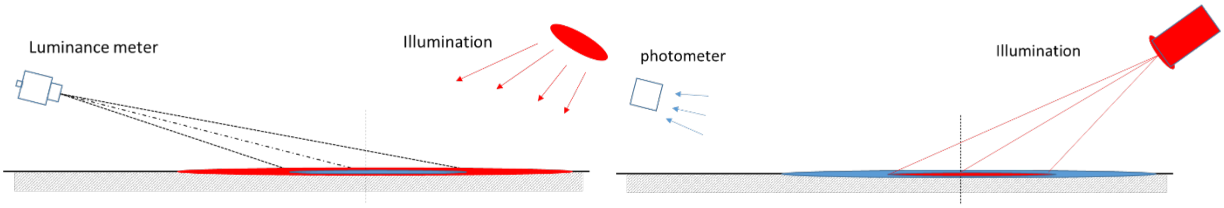


Figure 5 A schematic of a measurement setup. The field of view is limiting the measured area (left), The illumination determines the measured area (right).

A very important aspect of the measurement procedure is to identify the different factors affecting the measurement and contributing to the uncertainty. Ideally, those effects should be minimized as much as possible, but the remaining contributions should be evaluated. A strong collaboration among METAS and LNE, based also on the output of dedicated meeting attended with also INRIM, CEREMA and RISE, brough to the definition of the list of the measurement quantities, calibration factors and measurement uncertainty contributions of Table 9. The same output was used by LNE to build the LUMCORUN software for uncertainty evaluation. The uncertainty contributions are present in-situ and laboratory measurements, but most of them can be better controlled during laboratory measurements.

Table 9 shows the main uncertainty contributions.

Table 6. Measurement uncertainty contributions.

$k_{\mathrm{A}}\ (\beta, \varepsilon)$	Aperture effect (see section 3.2)
α_{L}	Temperature coefficient of luminance meter (unit: K^{-1})
α_{E}	Temperature coefficient of illuminance meter (unit: K^{-1})
ΔT_{T}	Temperature difference between calibration of illuminance/luminance meter and the measurement
$a_{\alpha}(\alpha)$	Angular error in $\alpha - q$ error contribution due to error on α: depends also on the sample reflexion characteristic, geometric effect
$a_{\beta}(\beta)$	Angular error in β – idem
$a_{\varepsilon}(\varepsilon)$	Angular error in ε – idem
$a_{\mathrm{E}}(\varepsilon)$	Cosine mismatch of the illuminance meter
$a_{\mathrm{a}}(\varphi, \phi)$	Error due to the tilt of the measured surface in respect to the coordinate system of the measurement device
o_{lin}	Nonlinearity
o_{stray}	Straylight Two cases: Goniometer in lab: stray light comes from the instrument light source Portable Goniometer: stray light comes from the instrument light source and the external environment (can be minimized if the light source is modulated)
o_{vlam}	*V*(λ) mismatch As the output quantity is a ratio of photometric quantities: To be considered: the difference of light source calibration spectrum and instrument light source spectrum, nevertheless a significant mismatch for both illuminance meter and luminance meter could exist, but if all light sources are the same type (e.g. Ill A for calibration and instrument) the error will be negligible given the neutrality of the samples. If it is not the case, to be considered: the differences of spectral sensitivity between illuminance and luminance meter weighted by the instrument light source spectrum. Also the difference of the transfer of the photometric scale is not considered as it is a ratio of two photometric quantities supposedly calibrated with the same scale.

Table 6. Measurement uncertainty contributions.

	Lamp instability (contribution depends on the measurement process and environmental conditions) a) Drift, which has been determined and therefore can be corrected b) Fluctuations, which have been observed, but cannot be corrected and therefore should be taken into account as a contribution to uncertainty
	Illuminance nonuniformity (contribution depends on the way the illuminance is measured) a) Drift, which has been determined and therefore can be corrected b) Fluctuations, which have been observed, but cannot be corrected and therefore should be taken into account as a contribution to uncertainty
	Luminance meter characteristics (excluding linearity): Contribution relative to the difference between calibration conditions and measurement conditions (source size effect, …) a) Drift, which has been determined and therefore can be corrected b) Fluctuations, which have been observed, but cannot be corrected and therefore should be taken into account as a contribution to uncertainty
	Overlap between detection field and illumination field: This is normally a problem which is handled in the instrument design, but if not done perfectly, it may produce drift or fluctuation.

4.3.4 Calibration and traceability – IoT Reference Materials

Reliable and traceable data of q and r coefficients are unquestionable needs not only for EU standards, but also for industrial and lighting engineering communities, clearly encouraged by new standards, new road surface materials and, above all, energy saving commitments and SSL opportunities. Absolute measurement methods require a direct calibration of luminance and illuminance meters in absolute units: these methods are usually used in laboratory goniophotometers. NMI have a well-established traceability chain for that photometric units. While relative methods are based on the calibration of RM, usually generic tiles previously calibrated in goniophotometers are used as RM. The INRIM knowledge on 3D printing, reference materials and material characterisation, together with the partners (CEREMA, AALTO, RISE, METAS) knowledge on the road artefact physical properties, allowed the project to develop dedicated RM based on IoT especially designed considering the peculiarities of road surfaces and engineered to ensure high stability (also in time) and easy alignment to provide high reproducibility and repeatability. Previously RM were actual road samples but they are really hard to manage and do not ensure stability and reproducibility, so they were not suitable for being used in the first intercomparison of luminance coefficient organized during the project. The choice of manufacturing RM by 3D printing, allowed to design RM considering two different approaches: one to ensure a RM with given reflectance properties so that the artefact has the same reflectance properties of CIE r-tables of CIE 144, the other to ensure a RM with the physical properties responsible of reflectance behaviour similar to those of road surfaces.

In the first case, design by reflection properties, the RM has for the given illumination angles and observation angle of [15] the same luminance coefficient as the given reference road type of [15]. Since the CIE reference table considers more than 100 different values, each RM can be designed to satisfy only few directions.

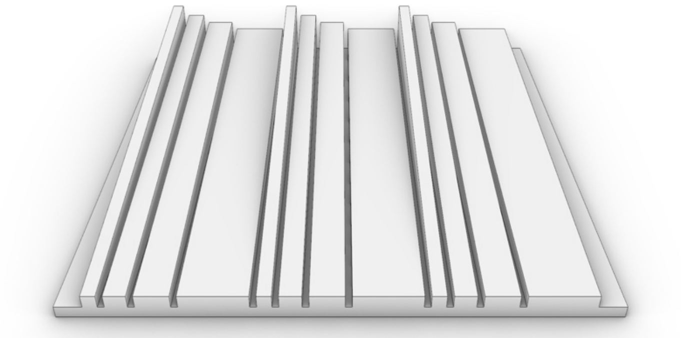


Figure 6 3D model of a RM having the normalized spatial reflectance distribution described by CIE 144 r-table C1 for β=0° and ε= 81°, 83°, 84° and 85°

In the second approach, design by road attributes, the RM is designed to have a reflected diffuse component, that in actual roads is due to binder or bitumen and a specular reflected component that is more linked to surface finish of aggregates.

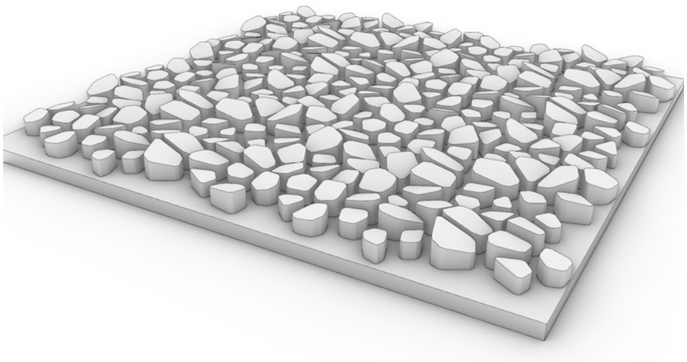


Figure 7 3D model of a RM having given solid attributes similar to road attribute for having a diffuse and specular reflectance behaviour

Both RM design methods were patented.

RM were designed for the actual application of being used to calibrate portable devices, since the usage of RM designed by reflection properties is not suitable for all available portable instruments, RM designed by road attributes have been used during the intercomparison.

Several printing materials have been tested to ensure the selection of the most useful reflectance behaviour, including spectral properties (grey reflectance with no fluorescence), printing angular accuracy and stability over time (including cleaning possibilities).

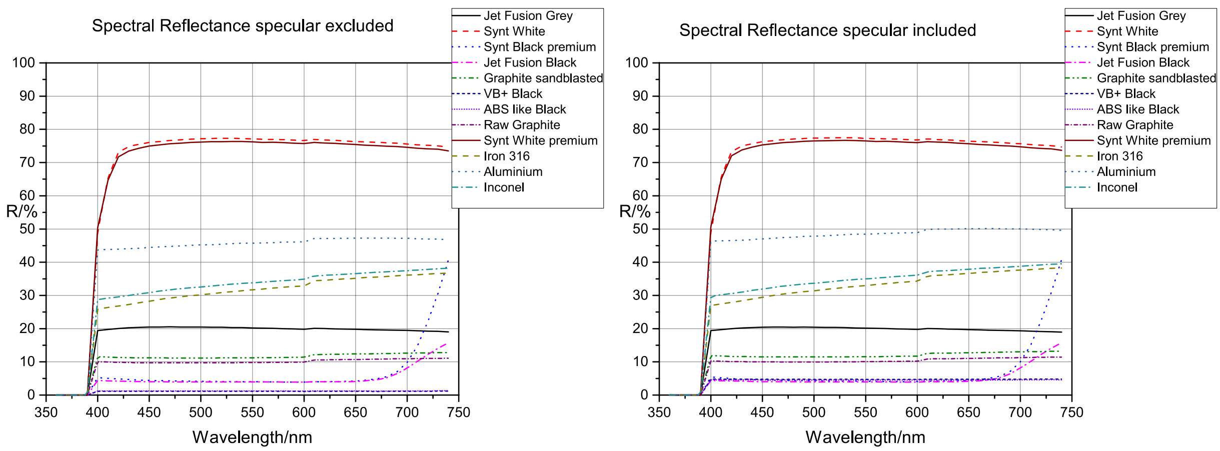


Figure 8 Reflectance behaviour of investigated 3D printing materials: Specular component included and excluded.

Two different sets of 3D printed RM were produced and used during the intercomparison: one set (Set A) is based on flat materials of given reflectance with matte and glossy behaviour, the other set (Set B) is based on artefacts with attributes similar to a road surface with matte and glossy behaviour made with the same materials of flat samples but with multifaces solid shapes of different heigh and size.

Set A RMs:

- 1 Artefact square flat of 20 cm by 20 cm in printed grey – matte, named DG000
- 1 Artefact square flat of 20 cm by 20 cm in printed black – matte, named DK000
- 1 Artefact square flat of 20 cm by 20 cm in printed black – glossy, named GK000

Set B RMs:

- 1 Wrought artefact with random point of size range 6 to 10 mm, high range 5 to 10 mm, 20% of flat surfaces printed in grey – matte, named DG110
- 1 Wrought artefact with random point of size range 6 to 10 mm, high range 5 to 7 mm, 20% of flat surfaces printed in grey - matte, named DG210
- 1 Wrought artefact with random point of size range 6 to 10 mm, high range 5 to 7 mm, 20% of flat surfaces printed in black – matte, named DK210
- 1 Wrought artefact with random point of size range 6 to 10 mm, high range 5 to 7 mm, 20% of flat surfaces printed in black – glossy, named GK210

The two sets have different measuring challenges related to their geometrical attributes: Set A will highlight linearity behaviour of instruments, expected discrepancies in the measurements will be related to linearity or severe calibration, including geometry issues, Set B has some samples with large height range and strong specularity, it will highlight discrepancies in the angular resolution of instruments, measuring area, linearity and calibration.

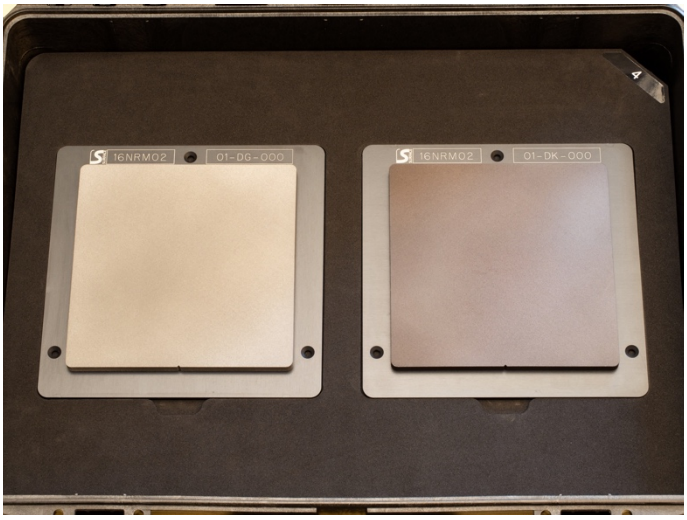


Figure 9 Pictures of two samples of Set A

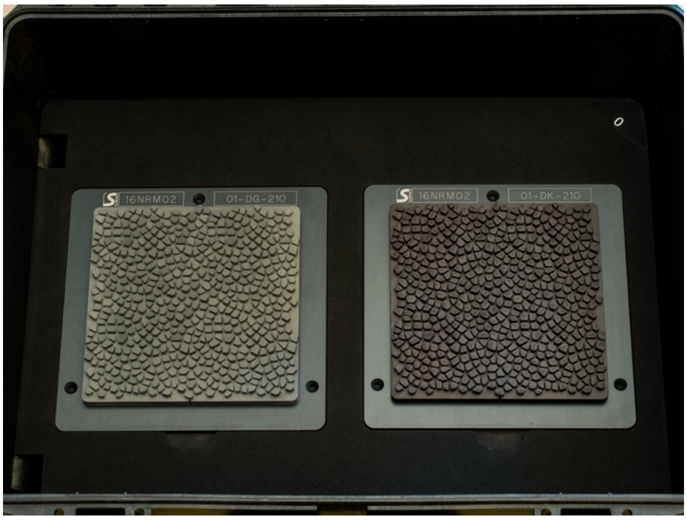


Figure 10 Picture of two samples of Set B

The metallic frames and the 20% of top heigh surface flat, allowed a good reproducibility in the positioning and alignment that brings participant repeatability around 1,5 % (including detector repeatability) with better performances of goniophotometers than portable devices.

The feasibility of IoT based Reference Materials (RM) has been proven. A RM kit was developed during the project and used during the first intercomparison on luminance coefficient: the RM kit and design have been patented. The design and usage of RM made during SURFACE is one of the first actual applications of IoT to metrology and has attracted the interests of Accreditation body as tangible application of normative on RM producers and future approach to RM based on IoT. More exploitation opportunities are related to additional investigations on printable materials properties, production process and printing accuracy vs material and printer. Further developments can be related to new opportunities for building a large funded action on Metrology of 3D Printing to investigate additional IoT applications of RM, and validation processes. Further investigation, especially on materials properties will allow the design of 3D printed materials with given r-table, this will help lowering the measurement uncertainty, and have additional impact on site measurement. Since the SURFACE RM kit has been used for the measurement intercomparison, the EU market benefits now of Certified Reference Material (CRM) for calibrating road surface measuring instruments.

4.3.5 Intercomparison on luminance coefficient using RM 3D printed and Uncertainty evaluation LUMCORUN software

The quantities to measure in the SURFACE intercomparison were: Reduced luminance coefficient r and Q0 and S1 values.

At least three measurements of each artefact and for each measuring geometry were carried out, which means taking out the reference material before the next measurement. The reduced luminance coefficient and Q0 and S1 values of the artefacts was measured following the measuring procedure of each laboratory for the given observation angles.

The intercomparison exercise is to measure the full r-table of all artefacts, or, since not all measuring devices are able to measure all $\tan\varepsilon$ and β lighting angles as reported in Table 3 of EN 13201-3, at least for all measuring directions of the instrument and (if possible) for the directions at which the values will compared (Table 6) and for α=1° of observation.

If the measuring instrument is able to measure additional and/or non-conventional directions it is requested to measure the samples also in the additional directions (Table 7).

Despite the coronavirus pandemic situation, with limited working capacity and access to laboratory, three different consortium members and two collaborators attended the intercomparison.

Table 7 Directions in which the measured values will be compared

Lighting Angles					Observation angle
tan□□	**□ / °**	**β/ °**		**Additional β/ °**	**α/°**
0	0	0	15	30	1
1	45				
2	63.43				
4	76				
6	80.5				
8	82.9				
11.5	85				

Table 8 Additional observation angles

Additional Observation angles □
2.29°
10°
20°

The pandemic affected a lot the laboratory engagements in testing the software LUMCORUN for the evaluation of measurement errors due to aperture effects: LNE software development and modulization knowledge merged with the METAS road characterisation expertise in testing the software, unfortunately for limited samples only because the pandemic situation. Therefore, the late LUMCORUN testing limited the analysis of the measurement discrepancies in the intercomparison values since the laboratories lacked strong uncertainty evaluation approach.

The RM artefacts with the best performances in the intercomparison so with the lowest dispersion among participants were for Set A DG000 and DK 000, for Set B DG210, DK210 and DG110. The smaller dispersion arrives with DG210 and DG110, evidence of linearity problems of portable devices at low values of black samples.

The intercomparison data analysis showed that instruments have a low compatibility index when only the standard deviation of data is considered, but the targeted uncertainty of 10% produces satisfactory results for the S1 Values, and for the lighting directions less affected by aperture effect systematic errors (namely tanε=0 and β=0) and ensures measurement compatibility (Figure 11) and for the most relevant samples.

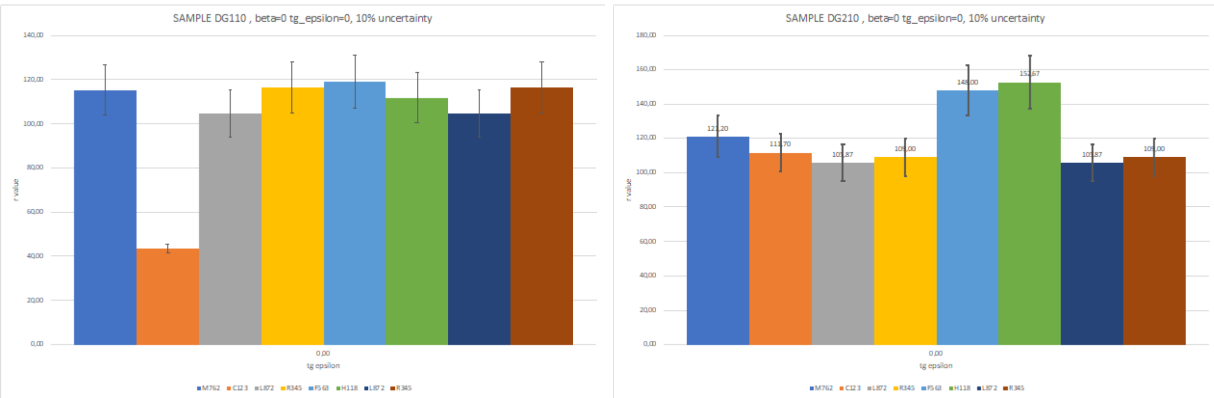


Figure 11 r value of DG110 and DG210 samples for tanε=0 and β=0: with 10% uncertainty and no systematic aperture effects corrections (note orange laboratory is an outlier)

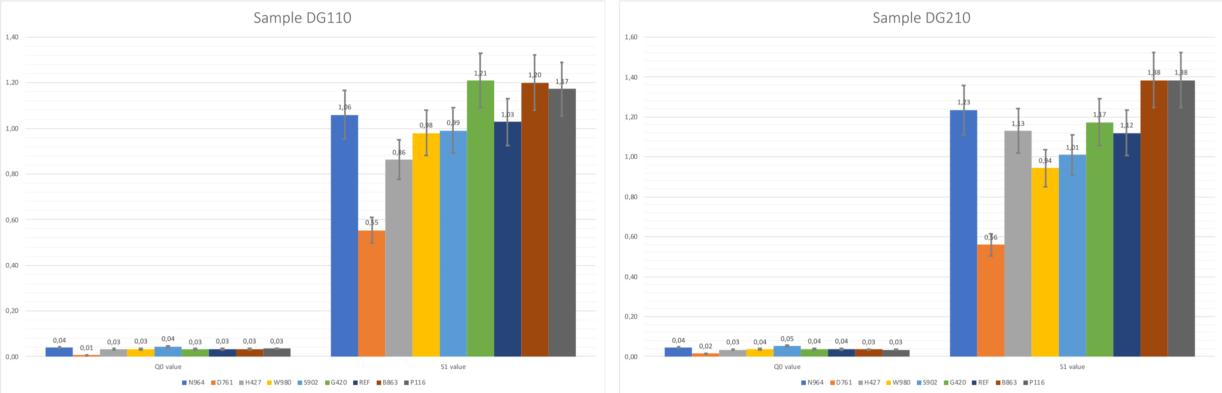


Figure 12 S1 values of DG110 and DK210 samples (note orange laboratory is an outlier)

The metallic frames, the 20% of top heigh surfaces flat, and the control on the manufacturing (and especially cooling after printing) process allowed a good reproducibility in the sample positioning and alignment, bringing participant repeatability around 1,5 % (including detector repeatability) with better performances of goniophotometers than portable devices.

LUMCORUN software highlighted that, since the extended apertures of viewed and illuminated area of the measuring devices, the measurement systems suffer from different systematic effects. Mainly related to the lens apertures, detector sensitive area and lit area. Using as input the instrument characteristics, the software is able to calculate these systematic effects. Unluckily, the software demonstrated that for high values of illumination directions (namely tanε >2 and β>15) measuring devices have the largest errors. This means that where the road pavements have the BRDF peak, the measurement errors are larger.

The use of LUMCORUN uncertainty calculator software is mandatory for a better understand of the instrument performances and subsequent data compatibility.

The program applies to uncertainty computation of portable and laboratory instrument measuring luminance coefficient of road pavements. The main aim is to provide an efficient computation of uncertainty contributions related to geometric errors or characteristics which require extensive calculation.

To evaluate the measurement uncertainty the GUM [34] starts from the requirement of defying a detailed measurement model, inclusive of all possible influence quantities and their uncertainties. The evaluation of how these quantities and their uncertainty affect the measurement is achieved by two approaches:

- full knowledge of the correlation among all uncertainties and of their reciprocal impact;
- simulation of the whole impact of the different uncertainty (usually by a Monte Carlo simulation).

This last approach is preferred when is too difficult or too time consuming the mathematical definition of all correlations among the different quantities of influence and this is the case of luminance coefficient measurement.

The program separately considers photometric errors and geometrics errors, the former depending mainly on non-geometric characteristics of the detectors and light sources (calibration, dark signal, linearity, temperature effect, stability, …) and the latter depending on geometric or spatial characteristics (detector aperture, goniometric angles errors, sample misalignments). The former can be calculated once, considering characteristics being constant at any measurement angles, and the latter must be calculated for each measurement angle to take into account the angle dependant effect of the BRDF on the error: aperture effect is negligible in a lambertian diffusing angular region but is critical around the specular angular peak.

Additionally, the software uses a simplified model of the measured surface (CIE r-tables) or actual measurements acquired with a laboratory device to account for the contribution dependent on the samples.

The uncertainty contributions can then be combined using uncertainty propagation rules as defined by the GUM. Given the diversity of instruments, the program could not cover all influent parameters for photometric errors and properly combine them; complementary calculations accounting for instrument's specificities should be designed and can be introduced as supplementary correction factors. Calculations tools are given for spectral mismatch and linearity error. For geometric errors most of the instrument cases are covered.

The general approach of the program is to use Monte Carlo Method (MCM), defined by the GUM supplement 1 But computation involving sampling of the sensitive detector area, light source emitting area and pavement sample area is not optimized for that case with random generation of spatial points, using predetermined regular spatial meshes enable to compute once all possible angles between point and then reuse them gaining processing time. The aperture effect is taken into account for any defined geometries and optical systems, by mean of a numerical integration of all the possible rays. To achieve faster computation, and for the five targeted pavement types, precomputed arrays of BRDF for relevant domain of α, β, ε and with a resolution of 0.1° are calculated. The BRDF values are then determined by linear interpolation. A difference between the integrated modelled BRDF and the modelled BRDF is computed and represents a systematic error. As this effect is strongly dependent of the incident angle (ε, β), the aperture effect is calculated for each incidence direction. The systematic error due to the aperture effect can be corrected by the mean of a relative measurement with a reference close to the targeted sample. The reference is used to determine correction factor k_A ratio of nominal (ideal) reflected luminance (without aperture effect) over the measured reflected luminance (with aperture effect).

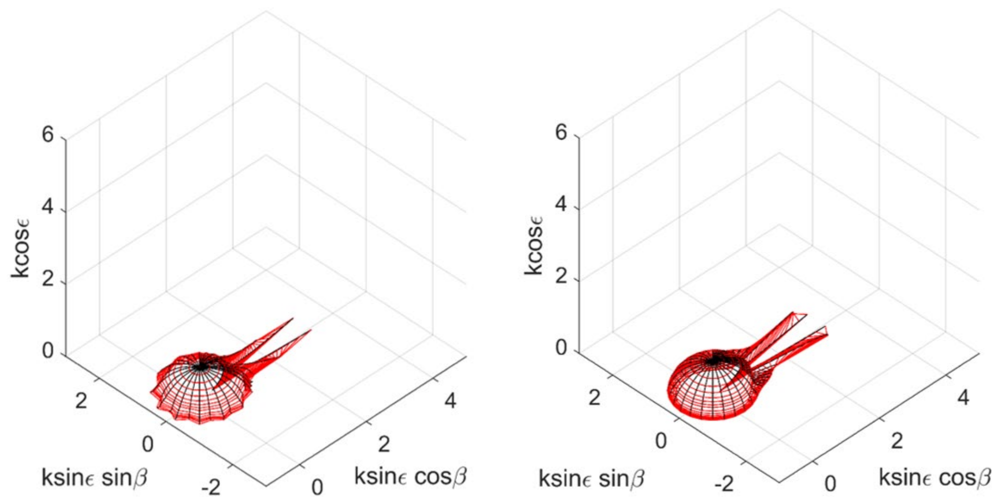


Figure 13. 3D representation and comparison of the results of the systematic error, with left) ratio k of the measurements with "ideal" and non-ideal instruments, and right) ratio k of the results of the software with "ideal" and non-ideal instruments. The illumination directions with β within 20° and with ε above 70° show the largest errors.

4.3.6 Summary of key research outputs and conclusions

Collaboration between the NMIs and the planned intercomparison; which was the first one ever carried out on luminance coefficient; ensured the necessary traceability and uncertainty of the European Metrology Infrastructure and instrument manufacturers. Furthermore, a dedicated Creative Commons (CC) open source software for uncertainty calculations was provided to the community and tested by the project partners. The measurement intercomparison was based on Reference Materials (RM) fabricated by means of 3D printing, representative of asphalt photometric performances. An intercomparison KIT made of two different sets of 3D printed RM was used: to test different measuring challenges related to geometrical attributes. The measurement method report of each intercomparison attending laboratory was also useful to the measurement guidelines. This objective was been met.

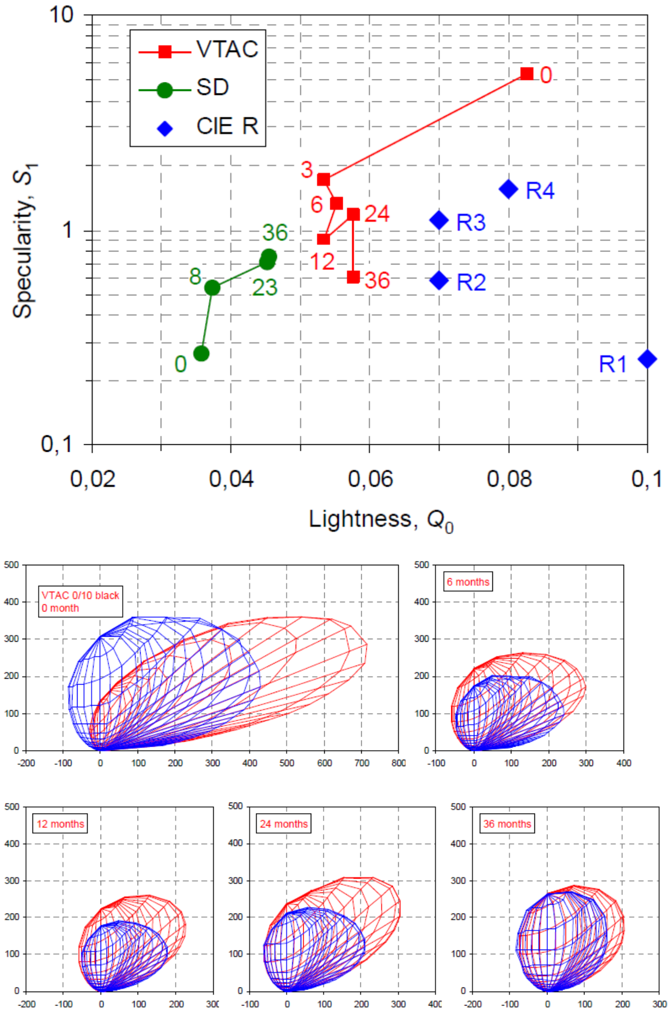
4.4 Pre-normative guidelines on additional aspects (Objective 4)

4.4.1 Pre-normative guidelines for photometric characterisation of road and pavement surfaces

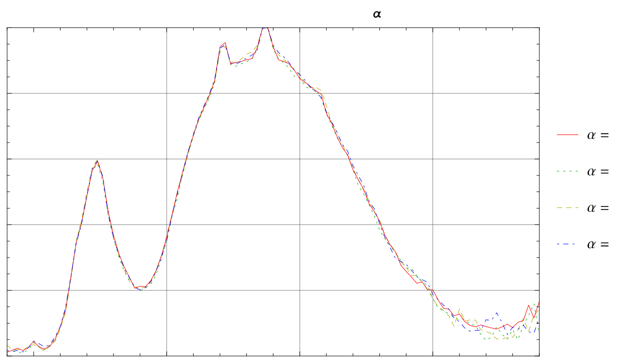
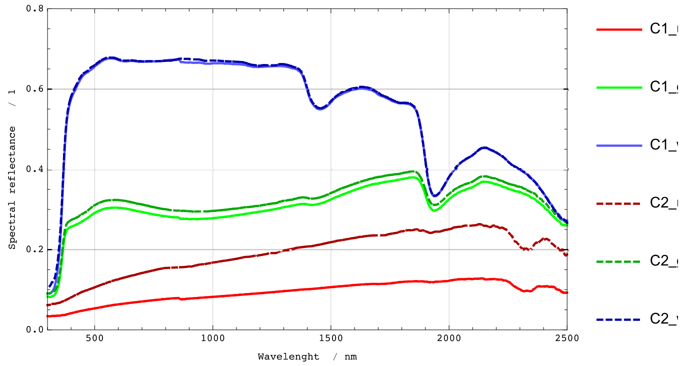
SURFACE activities were integrated with the CIE TC4-50 working plan, in particular pre-normative guidelines (namely deliverables D5 and D6) were put in a form to be incorporated directly into the new revision of CIE TR144. For this reason, SURFACE consortium chose to keep guidelines confidential in order to ensure the direct incorporation into CIE TR144

The following table resumes the SURFACE findings on additional aspects

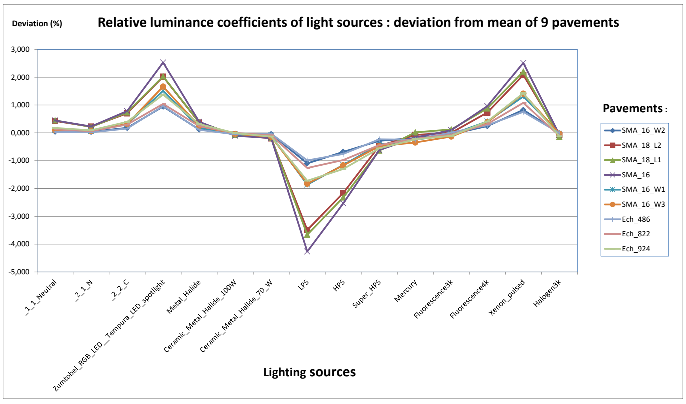
Property	Suggestions

<table>
<tr><td>Aging</td><td>
The effects of time and traffic density can be studied with portable devices.
The effect of ambient conditions without traffic was seldom studied and it is always difficult to isolate the effect of traffic from the time and ambient conditions. On the slow lane, dedicated to trucks, the aspects could be different because it has the heaviest traffic. Thus, if possible, the measurements should be done on each lane of circulation.


Impact of time (in months) on lightness and specularity for Very Thin Asphalt Concrete (VTAC in red) and Surface Dressing (SD in green) surfaces
Due to its exposure to traffic and meteorological conditions, the photometry of pavement changes very quickly in the first months, especially for raw pavements with bituminous binder. This specularity is really significant at a young age but fades fairly quickly under the effect of traffic and its exposure to climatic conditions
Additional suggestions in the confidential guidelines
</td></tr>
<tr><td>Wet</td><td>Road photometry of a pavement shall be measured in a dry state. In the presence of moisture or water, the variations of photometry are very important, depending of the quantity of water.</td></tr>
</table>

	The input of SURFACE project concerning wet pavements is a full state-of-the-art review If the road surface is inundated, the luminance coefficients are mostly dependent on the luminance and size of the light source providing the illumination [35] Additional suggestions in the confidential guidelines
Spectral	A large spectral library of road surface spectral reflectance is available online[36], typical reflection spectra show that concrete surface material exhibits the highest reflection in the visible wavelength range. Road materials like gravel and asphalt have lower reflectance, approximately 20 % and 10 %, respectively, which makes it possible to identify the pavement material used for roads. However, in the infrared wavelength range the reflectance of concrete and gravel pavements become equal at around 1 400 nm, the ratio decreasing towards longer wavelengths. This behaviour has obvious relevance in the environmental monitoring and urban heat island mitigation strategies[37]  *Figure 14. Example of the relative spectral distribution of the road radiance at different observation angles LED source.*  Figure 15. Spectral reflectance distribution of different road samples Some measurements have shown that around 450-nm wavelength, the reflectance of concrete and gravel are even equal. The reflectance of asphalt decreases at blue wavelengths and its impact on mesopic concept application was analysed too.

SURFACE focused also on the impact of different spectral distributions on nine different road pavements and their contribution to measurement uncertainty.



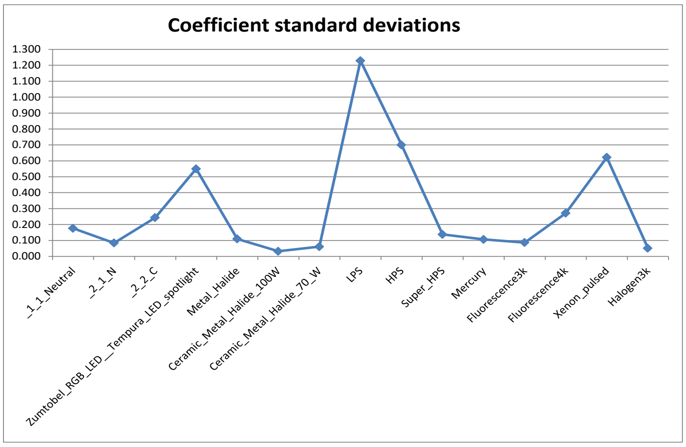


Figure 16. top) Relative deviations of the Relative Luminance Coefficient and bottom) standard deviations, of the set of road surfaces for the different light sources.

From the above figures, it is possible to say:

- RGB LED, Low-pressure Sodium, High-pressure Sodium and Xenon Pulsed light sources present the largest deviations from the mean, from −3 % up to +4 %, and dispersions with respect to pavements
- Metal Halide (CCT = 3610 K) and Halogen (CCT = 3000 K) light sources present the lowest deviations from the mean and dispersions with respect to pavements. Absolute deviation is < 0.15 % for halogen and ≤ 0.1 % for Metal Halide.
- Neutral LEDs present the lowest deviations from the mean (±0.3 %) and dispersions with respect to pavements and that for all light sources, deviations are comprised in the interval [−1 %, +2 %].

Adaptive systems

The knowledge of the road luminance coefficient is relevant at the design stage of not only road lighting systems, but also adaptive systems, where the actual values of pavement reflectance are useful for defining the design of the camera geometry setup, and for luminance calibration coefficient and data understanding.

At large viewing angles and short distances, the knowledge of Q_0 is enough, because of the Lambertian behaviour, but for

	comparison with the standard requirements and design values, knowledge of the road luminance coefficient is essential [38]. If the SURFACE proposal on new angles will be accepted, having adaptive systems able to measure luminance in a standard-compliant geometry will be easily achievable. Furthermore, as shown in [14], an adaptive system or at least smart lighting control are needed when new pavements are put on a site of an existing lighting system. This is especially true when associated with new LED luminaires, because the luminaire power, with a modern pavement, needs to be rescaled to satisfy the standard requirements, bringing clear energy advantages. In the definition of setup geometry of an adaptive system, it is not possible to define a single golden rule and a single optimal geometry. The definition is linked to the ability to compromise between camera performance, environmental conditions, accuracy needs, and pavement reflectance knowledge. Additional suggestions in the confidential guidelines

4.4.2 Summary of key research outputs and conclusions

This objective has been fully met. Guidelines produced during the project contained fundamental background on road surface parameters, detailed metrological requirements for portable and laboratory instruments with an emphasis on measurement parameters and geometries, and how these contribute to the measurement uncertainty. Regarding measurement procedures, both laboratory and on-site measurement procedures were detailed along with sample extraction, marking and handling, alignment, and documentation on laboratory measurements. For on-site measurements, the guidelines detailed: area selection, a description of a particular device for the evaluation of surface irregularities (that affects the most measurement geometries) designed and prototyped during the project, and data analysis. Additional aspects such as dirt, traffic, and spectral properties of the pavement and light sources, were also considered along with the measurement uncertainty and the influence of the various parameters is described. Furthermore, continuous engagement with the community of laboratories that perform measurements on road surface photometric properties, showed that the laboratories are unaware of the Guide to uncertainty measurement calculation (GUM) approach in the evaluation of the measurement uncertainty on q values. For this reason, SURFACE defined measurement models for the evaluation of the uncertainty on q values of simple application, which were tested by industrial laboratories during the intercomparison to ensure reliability and traceability of the results.

4.5 Reference data – SURFACE database – file format and CC policy (Objective 5)

4.5.1 Contributions to standard development

Road lighting designers adopt as de facto standard values, the r-table or the equivalent q values published in CIE documents. However, these data are based on measurements performed on concrete samples more than 40 years ago without traceability and uncertainty evaluation. Recent studies have shown that the use of CIE data as reference leads to large errors (on average over 30 %, but up to 50 % in worst case) on expected road luminance. Moreover, the photometric properties of road materials have changed over time considering new material components and laying techniques as well as the road lighting systems (i.e. LED sources, adaptive systems and smart lighting systems, and luminaires installed at lower heights).

A call lead by CEREMA was launched to establish the actual distribution of road surfaces families across Europe, to provide reference data on the most relevant actual roads to technical committees (objective no. 5). The SURFACE database of current road surfaces includes about 250 different types of road surfaces. Data have been classified in clusters, and a champion for each cluster was used as reference for road lighting calculations. The results highlight the differences among current road surfaces and published road data, especially in terms of LED road lighting systems.

SURFACE database considers only measurements made after 1990 and only by laboratory goniophotometer, so. Unfortunately, it was not easy for SURFACE to collect data because only few European laboratories are doing this type of measurements.

The chosen license assign to SURFACE data base is CC-BY-SA-4.0 (represented in orange in Figure). This license lets others reuse the work for any purpose, including commercially; however, it cannot be shared with others in adapted form, and credit must be provided to the SURFACE project. The license assignation has been strongly discussed among INRIM and OPTIS-ANSYS to select a license that will provide not limitation to open dissemination (NMI perspective) and commercial usage (ANSYS perspective).

	PUBLIC DOMAIN	PUBLIC DOMAIN	BY	BY SA	BY NC	BY ND	BY NC SA	BY NC ND
PUBLIC DOMAIN	✓	✓	✓	✓	✓	✗	✓	✗
PUBLIC DOMAIN	✓	✓	✓	✓	✓	✗	✓	✗
BY	✓	✓	✓	✓	✓	✗	✓	✗
BY SA	✓	✓	✓	✓	✗	✗	✗	✗
BY NC	✓	✓	✓	✗	✓	✗	✓	✗
BY ND	✗	✗	✗	✗	✗	✗	✗	✗
BY NC SA	✓	✓	✓	✗	✓	✗	✓	✗
BY NC ND	✗	✗	✗	✗	✗	✗	✗	✗

Figure 17 Seven CC licenses Ref. https://wiki.creativecommons.org. Surface used licence is CC-BY-SA-4.0.

Since an r-table is an extract of a Bidirectional Reflectance Distribution Function (BRDF), SURFACE chose to refer to file format suggestion from 16NRM08 funded project called BiRD "Bidirectional Reflectance Definitions" for harmonizing data presentation. An adaptation of the BiRD json format file especially for the needs of road photometry was proposed. The file ".json" has two main keys:

- A "head" containing information on sample and measurement, and values of configuration variables common to every included value.
- Measured data, configuration values and uncertainty values under "data" keys in a subsequent part of the file

In the SURFACE database, there are now 240 measurements which are shown in Figure 16, considering new pavements in red and pavements of more than 2-years age in orange. They are shown in comparison with the CIE standard *r*-tables data and an old database of 285 measurements done in the mid-1970s (1975)[39] on samples mostly from the Nordic countries.

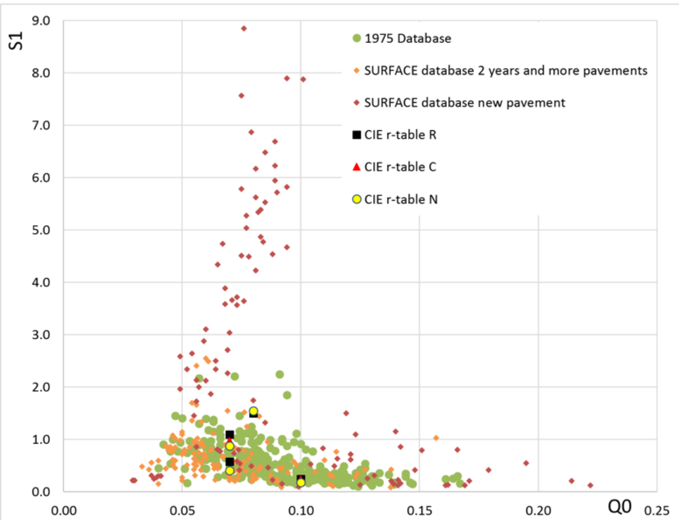


Figure 18 : Representation of SURFACE database divided in new pavements in red and 2 years and older pavements in orange. The CIE standard pavements and an old database (green) of 1975[39] are also presented.

considered the stabilised pavements (more than two years old) to exclude the initial specular effect. This excludes 102 tables from France (new or 1-year measurement) whose analysis was presented before. So, our final data set is composed of 138 Q_0 and S_1factors (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 18 compares Q_0 and S_1values of the original 1975 database with the CIE reference *r*-tables and the current SURFACE database composed of 138 stabilised pavements (in orange).

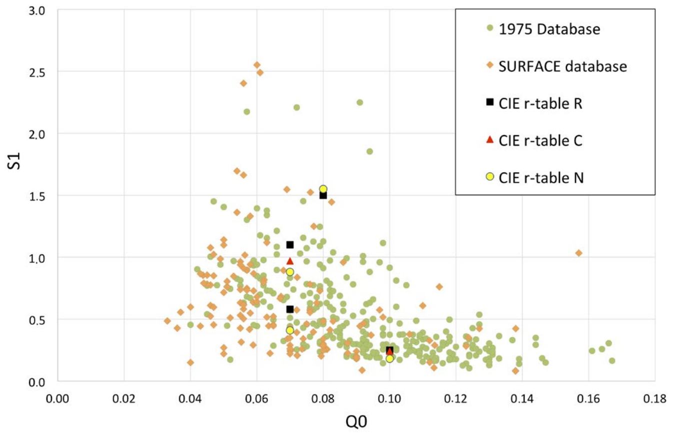


Figure 19 : Q_0 and S_1values of the original 1975 database, CIE road surface reference r-tables and the current SURFACE database composed of 138 stabilised pavements.

4.5.2 SURFACE Test Set

To compare performances a SURFACE Test Set was defined as a set of a given road and lighting class M3, a set of pavement data in the SURFACE database. The Test Set was established and tested in a publication, by partners INRIM, CEREMA, RISE and acknowledged subsequently by the whole consortium.

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

Figure 20 Geometry and lighting class of the road

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

The set of pavement data is made of five different *r*-tables representing median and extreme values among the available SURFACE database *r*-tables plus C2 CIE reference. The five of CURFACE Database represent:

- very light and diffusive road surface behaviour, 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 6 shows Q_0 and S_1 values of the C2 CIE standard *r*-tables and the values of the five selected road surfaces of SURFACE database. Figure 20 shows the reflective behaviour in space (*q* values) of the selected road surfaces.

Table 9 : Photometric characteristics of our selected data set.

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

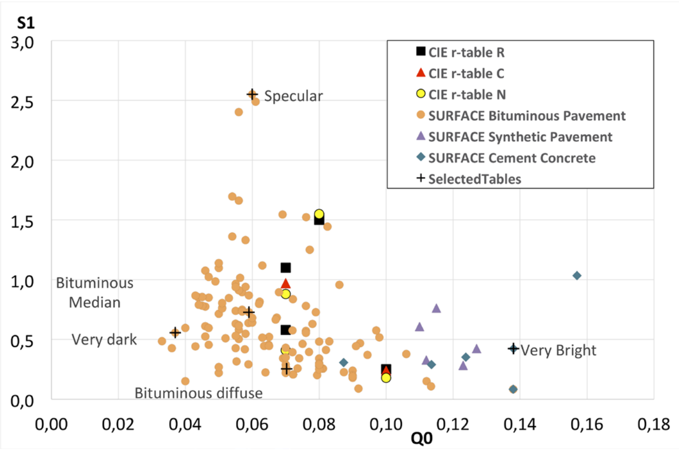


Figure 21: Q_0 and S_1values of road surfaces in Table 2 and the current SURFACE database composed of 138 stabilised pavements.

4.5.3 Impact on energy saving and safety

To provide effective data, two typical road lighting design cases were considered:

- CASE A: With pole distance optimized for the selected CIE *r*-table

  Design of a road lighting system using CIE reference table of the selected road (Table 6): the pole distance and luminaire setup are optimized for C2 road surface. It is the actual situation, when the pavement is very different from the selected C2.

- CASE B: With pole distance optimized for each *r*-table of SURFACE Database.

  Design of a brand-new system for a known actual road surface behaviour (Table 6): the position of the poles and luminaire setup are optimized for the given road surface behaviour. It is the situation of actual implementation of SURFACE database.

CASE A results:

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 rescaled values

Road Surface Type	q_{inst} [-]	Power Density Indicator D_P [mW/lxm^2]	Annual Energy Consumption Indicator D_E [Wh/m^2]	Difference on D_E vs. C2 [%]
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

Case A results show that erroneous evaluations can occur when the installed pavement differs from the selected CIE reference pavement: a relevant luminance underestimation (more than 40 %) for a very dark road surface and luminance overestimation for a bright pavement (more than 100 %).

CASE B results:

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

Table 12: Energy performance indicators of road lighting of Case B considering the actual luminaires power

Road Surface Type	q_{inst} [-]	Power Density Indicator D_P [mW/lxm^2]	Annual Energy Consumption Indicator D_E [Wh/m^2]	Difference on D_E vs. C2 [%]
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

Case B results describe a simplified short-term impact of the SURFACE project: lighting systems are designed and optimized for the actual installed road surfaces. To simplify calculations, results of Table 15 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 why 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 behaviour of road surfaces, with luminaire families optimized for specific Q_0 and S_1.

The results of both Case A and Case B show advantages in using very bright road surfaces: the fulfilment of the safety parameters for road users (with excellent uniformity) with large energy savings.

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 heating island, also emerged in the literature [37].

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. Unfortunately, the counter effect is a possible increase of light pollution.

4.5.4 Summary of key research outputs and conclusions

The objective has been met. The results highlight the impact of the SURFACE achievements in term of energy savings and visibility as improvement to safety conditions. The results have been regularly disseminated to relevant International and National Standardization Organizations, and mainly used: by CEN TC169/WG12 in the next revision of EN 13201 series (mainly part 3) or as an addendum; by CIE TC4-50 and TC4-51, for improving reference tables and guidelines; by National Standards Organisations, like the Italian UNI GL5 for standard UNI 11248, AFNOR for France, EVS for Estonia, SIS for Sweden and SNV for Switzerland; and by Laboratory Accreditation System. Moreover, all guidelines fulfilled through Objectives 2,3 and 4 were made fully available to CIE TC4-50

4.6 Overall summary of the results

- Database of actual pavement photometric performances
- File format for pavement photometric performances data (r-tables and/or Q0 S1 values and uncertainty) CC-BY-SA-4.0, json file format with descriptive header
- New measurement geometries, more linked to actual needs of road users (actual urban viewing conditions and stopping distances), easy feasibility, and linked to road marking geometries for a more uniform approach to road characterisation
- Two different pre-normative guidelines, with reference to measurement methods, sampling and on-site site selection, instrument performances, data report management, ageing, wet, spectral behaviour
- Software open access for the study of metrological performances of instruments for luminance coefficient measurements and measurement uncertainty evaluation
- First intercomparison on luminance coefficient with also the first usage of RM based on IoT
- Reference Materials (RM) patented and a gauge for site selection during on-site measurement campaign both based on Additive Manufacturing (3D printing) IoT shareable. Since RM were used in measurement intercomparison can evolve into Certified RM (CRM)
- Software open access for the study of metrological performances of instruments for luminance coefficient measurements and measurement uncertainty evaluation
- Feasibility study of a portable instrument based on previous knowledge on road marking characterization
- Strong involvement of SURFACE consortium member into SDO, especially CIE TC4-50 (Chair and technical secretary) to ensure that results will be incorporated directly into the new revision of CIE TR144
- Large bibliography database on the subject

5. Impact

SURFACE has produced 10 open access, peer-reviewed publications. The partners provided regular progress updates and presented project results to relevant standardisation bodies (such as CIE, ISO, UNI, AFNOR, GFSV and SIS) at TC meetings. Furthermore, the partners organised 10 workshops and training courses to promote key project findings and outputs to an external audience. Highlights include: the '*Too Smart, Too Light'* workshop on smart lighting, which was organized in March 2019, at Politecnico di Torino for 20 students, where a presentation of the results was also given to an audience of more than 200 people. Also, a symposium was organised on road surface characterisation which was held at the CIE Mid Term Session in Korea, allowing the project to enlarge the stakeholder committee and to raise awareness of the project results internationally. An additional symposium was planned near the end of the project for further dissemination of project results again under the aegis of CIE, during the CIE DIV4 meeting in May 2020. Due to the COVID-19 pandemic travel restrictions, SURFACE successfully organized 4 open access live webinars for the scientific and stakeholders communities instead. These webinars are available on the project website which was created in July 2017 and has been continually updated as new public information becomes available. It also contains a member's area with restricted access for project partners and collaborators.

Impact on Industrial and other user communities

The assimilation of the file format of luminance coefficient data and the data of *r*-tables of SURFACE database by the lighting engineering community and designers, was strengthened by the use of Creative Commons Policy and Open Access for the dissemination of all relevant materials and results and by the involvement of an IT company in the consortium. In June 2019, a joint meeting was organized with the EMPIR project 16NRM08 BiRD where BiRD project partners presented the file format for BRDF (Bidirectional Reflectance Distribution Function) data sharing to ensure a common European Approach to luminance coefficient and BRDF data presentation. Furthermore, interest in the production of RM and the concept of IoT RM for luminance coefficient has steadily grown due to the promotion of key project outputs and outreach activities undertaken by the project (such as the largest Energy Saving event in Italy, Ecomondo 2017 and the exposition A&T (Automation and Testing) in Torino in 2018, 2019 and 2020). The design and usage of RM produced in SURFACE is one of the first actual applications of IoT to metrology and has attracted the interests of accreditation bodies (such has ACCREDIA, the Italian Body for accreditation) as tangible application of normative on RM producers and future approach to RM based on IoT. The RM kit and design have been patented. More exploitation opportunities are related to additional investigations on printable materials properties, production process and printing accuracy vs material and printer. Further developments can be related to new opportunities for building a large funded action on Metrology of 3D Printing to investigate additional IoT applications of RM, and validation processes. Since the SURFACE RM kit has been used for the measurement intercomparison, the EU market benefits now of Certified Reference Material (CRM) for calibrating road surface measuring instruments.

In December 2018, a delegation of the collaborators Panasonic and Nexco-RI visited INRIM and Cerema for a technical meeting focused on portable instruments development, SURFACE new geometries and their introduction to Japan. It was the starting point of an active with engagement of Japanese collaborators in the consortium activities and subsequent involvement in the SURFACE Webinar. Indeed, that was an additional sign of the EU leadership in the field of road surface metrology: the state of art of research, measurement methods and devices (large majority of currently available instruments are in EU, and the few available outside EU, most have been developed in EU). The project attracted interest of the ADAS (Advanced Driver Assistance Systems) testing and producers communities: SURFACE representative is among IEEE P2020 (Automotive Image Quality) group, and invited to the largest European event on ADAS (September 2019, AutoSens) to attend a panel on the optimization of roads for vehicle perception applications through improvement on road design, characterization, and maintenance. The investigations on the improvements necessary to adapt a road marking commercial measuring device to road surface characterisation have led to connections between global descriptors or reflective properties of road marking and road surface. This will ensure future development of a new portable measuring device on the market and support the implementation of EN13201 on-site *q* measurements.

Impact on the metrology and scientific communities

At the beginning of the project, an analysis of actual NMIs involvement on road surface characterisation was carried out via the BIPM (Bureau International des Poids et Mesures) website on the KCDB database devoted to intercomparisons (Key Comparison Database) and gave no results on road surface intercomparison. In the KCDB only eleven Key Comparisons have been ascribed to materials properties, nine of them belong to regular transmittance and two to diffuse reflectance, none was about luminance coefficient evaluation. The software for uncertainty evaluation developed during the project along with the intercomparison results will improve the metrological capabilities of NMI and stakeholders (collaborators) goniophotometers and portable devices for road surface characterisation and, by consequence, the European metrological services on road lighting and material characterisation. It is anticipated that the EU market will benefit from the uncertainty evaluation software that has been developed and validated during the project.

Impact on relevant standards

The project supported CIE TC4-50 in the revision of TR 144 and contributes to the standards development works of the technical committees CEN TC169/WG12.The project has been introduced to CIE Division 4 and CIE TCs TC4.50, TC4.15, TC 4.51 at the CIE-meeting in October 2017, May 2018, June 2019, May 2020 and the TCs members strongly supported the TCs involvement. The CEN TC169/WG12 Chairperson attended the project live webinar and invited consortium member to present achievements on new geometries and road surface database at the first meeting of TC169/WG12 for EN 13201 revision.

During the project, at each CIE DIV4 meeting (October 2017 in Jeju, May 2018 in Berlin, June 2019 in Washington) the project results were discussed. Meanwhile at CIE TC4-50 meetings held concurrently, project actions were constantly planned and integrated with the CIE TC4-50 document revision. On 25th of May 2018, at Berlin TU University, after the CIE Workshop “A new Vision of Visibility in Roadway Lighting” the consortium organised the first stakeholder meeting. Around 20 stakeholders attended the event. Stakeholders acknowledged the main results presented by the consortium: new geometry for road surface characterisation based on three different observation angles (instead of only one as in the current reference documents), new reference source for spectral calculations of road surface behaviour (available reference documents do not consider spectral peculiarities) and RM for the planned intercomparison. On June 2019, at CIE quadrennial session in Washington, the second stakeholder meeting was organised to present key project achievements: the database of the *q* values of current road surfaces, the SURFACE *test set* and their impact on the energy saving and visibility, a preliminary version of RM set was also presented to stakeholders community.

The optimised geometries (Objective 1) were presented and acknowledged during the second project stakeholder meeting in Washington, USA (which coincided with the 29th CIE quadrennial session) and at CIE TC4-50 meeting (in June 2019).Although, the CEN TC169/WG12 was not active due to the revision of the current standard EN13201 which should have started in 2020, in October 2019 they met to resolve some discrepancies in EN 13201-3. During this meeting the SURFACE research results were presented and the EN TC community were informed of the expected achievements. In June 2020, the CEN TC169/WG12 Chair attended the SURFACE Webinar and the continued interest in the project’s outputs was affirmed, as a result a project partner was invited to next available CEN TC169/WG12 meeting.

Longer-term economic, social and environmental impacts

Road lighting consumption is about 6-7% of a country’s total electrical consumption, but for a given municipality can be as high as 50% of the whole electrical consumption. More efficient lighting design based on SSL (Solid State lighting) and Smart Lighting can potentially save up to 70% on lighting energy, lowering the CO_2 impact, and allow the development of smart cities. These results can be achieved only with better design based on more reliable data on road surface characteristics harmonized with current road lighting standards, in order to provide higher visual quality ensuring safety conditions to all road users. The *SURFACE* reference data of actual (and upcoming) road materials will allow lighting designers to meet the normative energy savings and quality parameters as per the EU’s commitment to cut energy consumption by 20 % by 2020. It will also strengthen the turnover of old lighting luminaires into new SSL luminaires and the introduction of adaptive and smart lighting systems allowing bigger energy savings.

EU Road Safety Programme aims to cut road deaths in Europe between 2011 and 2020 by about 40%. The *q* reference data of actual road surface are an unavoidable need for the design of safer roads and the implementation of EU Road Safety Action trough the improvement of EU road Infrastructures, including intelligent and Smart roads and road assessment. Additionally, the proposed geometries are actually based on the different road-users and their needs, viewing conditions, road typologies (urban road, extra-urban road) and the related stopping distance. This will provide the basis for future investigations based also on subjective testing and ensures that the road luminance design and evaluation is made accordingly to actual users’ needs with an effective road safety increase.

The SURFACE *test set* demonstrated the impact on visibility and energy saving when using actual road surfaces of the SURFACE database, instead of outdated data represented by CIE *r*-tables. The use of actual SURFACE database *r*-tables and LED lighting system highlights the relevance of pairing light road surfaces and smart lighting system to achieve the best results in energy saving and visibility. The use of SURFACE data can lead to energy savings that, for bright pavements, can be up to 27% in brand new lighting systems, compared to using current (and old) CIE database. The energy saving can go up to more than 50% with the concurrence of new pavement installation and of Smart Light controllers for ensuring the compliance to normative visibility requirements in case of new pavement installation on existing lighting systems.

6. List of publications

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Greffier F,Muzet V, Boucher V, Fournela F, Dronneau R., Use of an imaging luminance measuring device to evaluate road lighting performance at different angles of observation. https://doi.org/10.25039/x46.2019.OP75

P.Iacomussi, Metrology impact for ADAS, Imaging IS&T 2020 conference. https://doi.org/10.2352/ISSN.2470-1173.2020.16.AVM-202

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

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