16th IMEKO TC4 Symposium
Exploring New Frontiers of Instrumentation and Methods for Electrical and Electronic Measurements
Sept. 22-24, 2008, Florence, Italy

On road measurements of the luminance coefficient of paving

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List of topics of interest: Optical Wavelength Metrology

***Abstract*-**The paper describes the design phase of a portable gonio-reflectometer for the measurements of the reflection properties of road paving directly on site. The importance of these measurements is highlighted, then the measuring procedure is briefly described together a presentation of the organization of the instruments itself and the design criteria. Attention is focused on the positioning of the light sources exciting the surface under analysis and on the errors which can appear in the evaluation of the performance of a road lighting plant designed on the measurements realized by the portable gonio-reflectometer, in particular.

I. Introduction

If the capability of distinguishing colour is ignored, the human ability of obtaining useful information from a visible frame depends on our skill in discriminating portion of the observed picture with different luminance. An object on the road is identified as something different from the road itself if it exists a luminance contrast between the object surface and the road surface, i.e. it is either lighter or darker than the road. The luminance contrast depends on both the light reaching the object and the road and on the way the light is reflected toward the observer. Therefore, the reflection properties of the road surface are of primary importance when the road lighting installations is designed, using the right parameters in describing the road will allow a best visibility for drivers. A good knowledge of reflection characteristics of the road paving allows a more efficient positioning of the luminaries, defining a luminance distribution on a road fulfilling national and international standard and optimizing the plant and energy cost, reducing light pollution, consequently [1].

A very good description of the emission characteristics of the luminaires is provided by the manufacturer giving the luminous intensity in many half planes with a high angular resolution within each half plane. Therefore, the light source is well known when the design of the light plant is approached.

The reflection characteristics of the road depend on the angles of light incidence and of observation: many measurements are required to allow a satisfactory lighting system design, in fact, each point on the road is illuminated from more than one luminaire and observed from several directions. A complete description is provided by the luminance coefficient [2], [3]

$q(\alpha,\beta,\gamma) = L(\alpha,\beta,\gamma)/E(\beta,\gamma)$,

the ratio of the observed luminance (L) over the illuminance (E) in the considered point. The quantities depend on the observing and incident angles α, β and γ, defined in Figure 1. Usually the behaviour of the road surface is taken into account by using standardized r-table, there the reduced luminance coefficient, multiplied by a factor 10000, is represented, in the place of the luminance coefficient q, according to the definition

$r(\beta,\gamma) = q(\beta,\gamma)\cdot\cos^3\gamma$

It is a function of the angles β and γ defining the position of the luminaire, according also the position of the observer, for a given observation angle , $\alpha = 1°$ as sketched in Figure 1.

A synthesis of the r-table is given by two global parameters: the average luminance coefficient Q_0 and the specularity factor S_1. The first is the average value of the luminance coefficient q over a solid angle (Ω_l) starting from the road element under analysis and including all the light rays providing a significant contribution to the luminance of the element. It expresses the ability of surfaces in reflecting the light, its brightness.

$$Q_0 = \int_{\Omega_l} q(\beta,\gamma)d\Omega$$

The second is the ratio of two values of the reduced luminance coefficient for two different directions of the incident light:

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

It describes in synthesis the “way” the surface reflects the light.

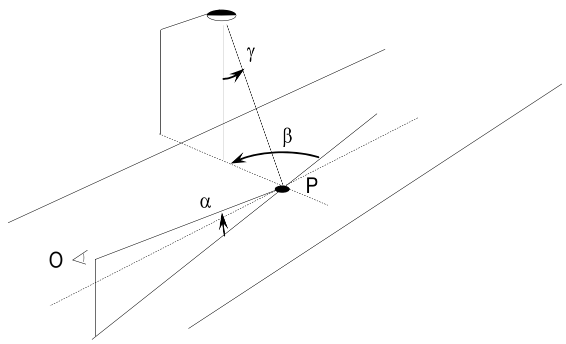

Figure 1 Reference coordinate system for road surface analysis

II. Focusing the problem

The best way of knowing the response of the paving to the light is measuring the luminance coefficient along the required direction of the light ray, but, doing that, it presents some difficulties. An accurate way to measure the reflection characteristic of a surface is placing one or more samples of the surface on a gonio-reflectometer, in a laboratory, and analyzing its reflection for whatever incident and observing directions [4], [5]. This procedure requires the sample is extracted from the road. An operation quite expensive and delicate, in fact deforming the upper surface can reduce the efficacy of the results. Owing to the not negligible cost of the sampling operation, the number of extractions has to be reduced. They should be significant for the behaviour of the whole road and should be picked up in different places on the track. The number of sample is a trade off between the accuracy in describing the surface and the cost of the extraction. Furthermore, the road to be lit is often under construction or that the reflection characteristics of its surface have not reached their stability, it will be obtained only after some month of exercise.
When it is not possible to obtain a characterization of the paving, the standards suggest the measurements, by a road reflectometer [2], or an estimate of the two global parameters Q_0 and S_1. Then a standardized table of reduced luminance coefficients should be chosen on the basis of the specularity factor, thus assuming a distribution of the luminance coefficient. The table coefficient should be scaled by the ratio of the measured, or estimated, average luminance coefficient over the coefficient Q_0 specific for the chosen table.
Unfortunately, designers usually estimate the specularity factor on the basis of the material used for the surface, but do not either measure or estimate the average luminance coefficient, and found the design of the lighting plant on the table printed on the standard only. Usual approximations take advantage from the reduced luminance coefficients of the standardized CIE R and C classes, but they often do not apply any scaling of the tables by the actual average luminance coefficient of the road under study. The results of the design are either too high values of the average luminance of the lightest paving surfaces, with a correspondent waste of electric power, or a deficiency on luminance, for the darker ones, with a consequent reduction of the visibility. In both the cases, the differences between the real and the required luminance values can reach about 50%. If too low luminance values are obtained, the problem can be repaired by changing the lamps with more powerful ones, causing an excessive installed power arriving at a peak of about 100% in extraordinary situations [6]. These evaluations prove the importance of knowing the real behaviour of the paving, both to assure safety for the road users and to avoid waste of power.

III. Approaching the problem

The problem can be faced by the use of a portable instrument placed on the road, directly. Even if the measurement will be obtained in less controlled conditions, a larger number of samples could be picked up

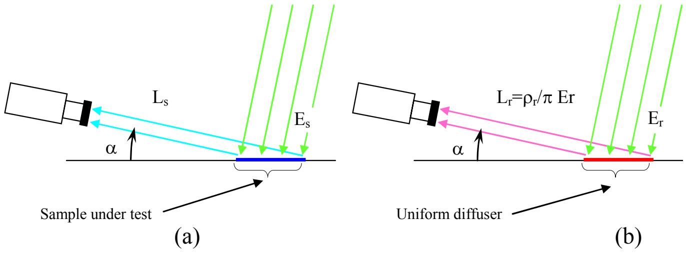

Figure 2 Luminance measurements on the sample under test (a) and on a diffusing sample used as reference (b)

being more representative of the status of the road surface. Furthermore, the lack of information on the road under construction could be covered partially by mapping the surface of the roads of the area (district, municipality, ...) where the new road will be placed, they should have reflection characteristics very close to the new one, in fact the same material, coming from the same quarry, should be used, probably. A response to this issue was given by developing an instrument capable of measuring the reflection characteristics of road surfaces on site [7]. It is has light sources at four different angle, lighting a small portion of the road surface and nine calibrated cell with a small black tube acting as luminance meters. The lights are fixed and the cells can rotate altogether around the lit portion of the road measuring the luminance in the β range between 0° and 150°. A measurement of the luminance coefficient for various incident and observation angles is obtained finally. Then the authors propose a method to infer the values of the correspondent r-table, according to a mathematical model of the road surface. The project here described wants to overcome the mathematical model and proposes a direct measurement of the luminance coefficient and therefore of the r-table. Furthermore it does not require a calibration of the luminance meter used in the measurements: the reflection characteristic of the road is obtained by a method of comparison, weighting the reflected light from the road against the incident light.

IV. Design of the measurement system

The presented project is the evolution of a previous system allowing the measurement of the characteristic of road surface on site [8]. In both the projects the observer is placed at the angle α=1° with respect to the horizontal plane, so as the measurement considers the reflected light as it is seen by a driver on the road, directly. The detector is in a fixed position while the light source can rotate all around the sample.
The sample under test is lit by a stable source and observed by a CCD scientific grade camera provided with a photometric filter and a high dynamic range. The use of a CCD, in the place of a photometric cell, allows to identify the potion of the road surface under analysis, better, selecting the received light from the sample under test from that coming from other unwanted, but unavoidable reflections. The camera observes the sample under analysis and a uniform diffuser, one at a time, lit by the same source as in Figure 2. The luminance (L_r) of the diffuser is proportional to its illuminance (E_r) according the following expression:

$$E_r = \frac{L_r}{q_r}$$

where L_r is measured luminance and q_r is the luminance coefficient of the diffuser measured in an accurate way in the laboratory.
As the illuminance on the road sample and on the diffuser is the same, the luminance coefficient of the road, at the observing angle α, can be evaluated:

$$q = \frac{L_s}{E_s} = q_r \frac{L_s}{L_r} \qquad \text{(when } E_s = E_r\text{)}$$

The result is independent from the absolute calibration of the CCD luminance meter reducing the uncertainty on the luminance coefficient.
In the previous mobile gonio-reflectometer the source can cover all the β and γ angle identified in the standard r-table; the lighting system was simple and cheap, but it was cumbersome, as the halogen lamp had to be placed far from the sample to grant the light rays are within a narrow solid angle, the detector had to be realigned for every sample, and it worked in manual way, being too much time consuming.
A sketch of the new system is presented in Figure 3. The light sources are obtained by white LEDs mounted on an arc revolving around the normal passing through the centre of the portion of road surface under test. The arc rotation is obtained by a step motor and is controlled automatically defining all the required angle of incidence β. On the other hand, with the aim at reducing the complexity of the system the light sources are fixed on the arc and switched on and off in turn.

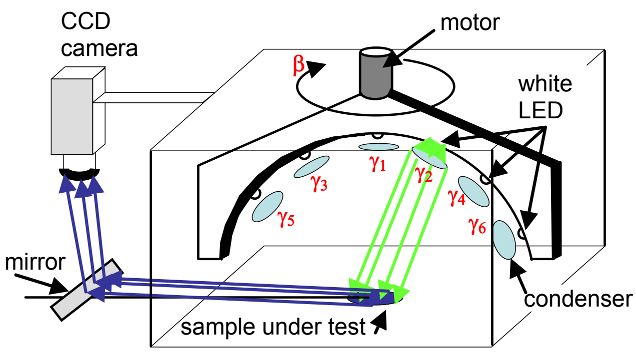

Figure 3 Schematic view of the new gonio -reflectometer

The sample dimension is defined by the diameter of the light spot on the road. As the observing angle is very small (α=1°), the image of the sample on the CCD is a highly elongated ellipse, the minor axis of which should be at least about ten pixels to allow averaging the measured luminance over a sufficient number of values. Supposing the dimension of the system of the order of one meter, the diameter of the sample should be about 10 cm. It is also the dimension of the plane-convex lens used to collimate the luminous flux emitted by each LED, so reducing the spread of the direction of the ray reaching the sample.

From the choice of using fixed light sources on the arc, the dimension of the light condenser and a side of the system about one meter, the number of selectable γ angles is at maximum equal to six. Therefore, completing the r-table requires an interpolation of the directly obtainable values of the luminance coefficient, an estimate of the uncertainty introduced by the interpolation will be presented in the paper. The choice of the realized lighting angles γ was done analyzing the behaviour of the reduced luminance coefficient of standardized r-table for each fixed value of the β angle. In particular the variations of r was considered, they are presented in Figure 0 (a) and (b) for table representing asphalt and concrete surface, respectively. The concrete surface presents a quite regular behaviour not very dependent on the β values; on the contrary the asphalt surface has a behaviour dependent form β and sudden variations of the derivative of r are more frequently found when the dependence from γ is considered. In both cases the most significant variations happen for small γ angle, this induced to concentrate the measures of the luminance coefficient in the first range of γ angles (tan γ= 0 0,5 0,75 1,25 2 4), where r assumes the highest values, too.

V. Consequences due to the sampling of the r-table

Here above some bonds and the correspondent solutions are presented regarding in particular the choices for the light sources and their positioning, as it is considered critical for the design of the gonio-reflectometer and for the significance of the obtainable results. The consequences in terms of the error in reconstructing the table of the reduce luminance coefficient are now considered. Furthermore, when a design of a road lighting plant is based on the road characterization performed by the portable gonio-reflectometer, it is worth of interest to estimate the propagation of the error on the local and average calculated luminance of the paving.

During the operation of the gonio-reflectometer, the portion of the road surface is not lit and observed at all the incident angles used to describe an r-table, therefore an error is expected in the use of the measured data. It depends on the ability of interpolating the acquired data and of extrapolating them over the larger γ angle considered by the instrument. For this issue, the values of the reduced luminance coefficient are approximated by zero at the largest angle γ (tan γ = 12), for every polar

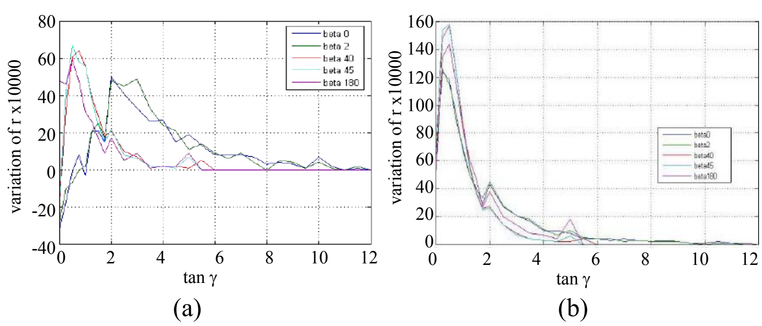

Figure 4 variation of the reduced luminance coefficient versus tan γ for an asphalt surface (a) and for a concrete surface (b) angle β. In the follow, the error on the estimated reduced luminance coefficient, due to the sampling and the interpolation, is considered and the effect of its propagation on luminance values is calculated. In the cases hereafter presented the simpler linear interpolation is used.

A. Errors the r-table values

The two CIE r-table C1 and C2 are here taken into account as examples, again. They present significantly different shapes and evaluating the errors on their reconstruction could give a valid estimation also for other road surfaces. For both the classes, the largest error values appear in the range of tan γ between 2 and 4, for every β value. At tan γ larger than 4, the errors are due to a lack in the extrapolation method, which is used for simplicity reasons in this presentation. These errors could be reduced by a better description of the behaviour of the surface reflection by a more physical model. On the whole, the maximum error in the reconstruction of the table is lower than 5% of the maximum value of the reduced luminance coefficient and lower than 10% for the C1 and C2 classes, respectively

B. Errors on the local and average luminances

The r-table represents the luminance of a surface lit by a source with a uniform intensity for every direction, located at unitary distance. To stress the effect of the error in estimating the r-table, the luminance of a road surface is evaluated, when it is lit by a real lighting plant. The effect of the approximation is considered in terms of the local and mean quantities. The example takes into account a road with two lanes and a unilateral layout of the luminaires, the used model is a common commercial one with flat glass. The luminaires are placed at a high of 8 m and a spacing of 20 m.
The local error is always not larger than 0,43 cd m^{-2} for C1 road class and not larger than 0,25 cd m^{-2} for C2 class, versus an average luminance of 2,49 cd m^{-2} and of 1,46 cd m^{-2}, respectively.
It is considered of interest to analyze the approximation effect also on average quantities describing the road lighting: average luminance $(\overline{L})$, luminance overall uniformity (U_0), luminance longitudinal uniformity for both the road lanes (U_{l1} and U_{l2}) are presented in Table 1,together with they errors (Δ•) due to sampling and interpolating possible measurements of the luminance coefficient.
For both the road classes the relative error on the average luminance ($\Delta\overline{L}/\overline{L}$) is reduced to 5 %, which can be considered an acceptable result in designing a lighting plant: it has to be taken into consideration that many other parameters influence the accuracy of the simulation result and, then, the implementation of the plant. Considering only the implementation, an important contribution to luminance uncertainty is due to the accuracy in positioning the luminaires; the variability of the road surface characteristics and how much the analyzed road is representative for the case related to the design. For the same reason, also the errors on the uniformity are supposed adequate to the precision of a design of a road lighting plant. The calculated errors are valid for the specific lighting plant and paving characteristics, similar results are expected for other plant configuration and reflection properties of the road surface.

VI. Effect of the internal stray light

A portion of the light emitted by the LEDs is collimated by the lens on the sample, while another not focalized part is dispersed on the protecting cover of the goniometer and than scattered in all directions, also towards the portion of the road surface under test. Furthermore, also the light hitting the sample directly from the condenser lens is scattered towards the protecting cover and again reflected back onto the sample and so far. The luminance observed by the CCD luminance meter is due to the direct lighting from a defined incident angle plus a bias error due to the light coming from all the directions around the sample, approximately. A rough estimate for the amount of this error can be done considering the ensemble,

	$\overline{L}$	$\Delta\overline{L}/\overline{L}$	U_0	ΔU_0	U_{l1}	ΔU_{l1}	U_{l2}	ΔU_{l2}
	cd m-2	(-)	(-)	(-)	(-)	(-)	(-)	(-)
C1	2,49	0,05	0,72	-0,02	0,60	-0,005	0,82	0,034
C2	1,46	0,05	0,76	-0,02	0,77	-0,005	0,90	-0,04

Table 1: Effect of the reconstruction error of r-table on the average quantities describing a lighting plant

composed by the portion of the road under the instrument and its protecting cover, as a diffusing sphere. The input luminous flux on this sphere is the sum of the flux reflected by the portion on the road under analysis plus the portion of the light coming from the LEDs, directly, which is not gathered by the condenser lens, but hits the protecting cover.
For a prefect diffusing sphere, the luminance (L) assumes the same value for whatever is the portion of the sphere internal surface, it is given by

$$L = \frac{\Phi}{\pi A_s} \cdot \frac{\rho}{1-\rho(1-f)}$$

where Φ is the luminous flux put in the sphere, ρ is the reflection coefficient of the surface of the sphere, f is the ratio of the sphere aperture area over the total sphere area A_s [9].
With the aim of simplifying the error estimate, the behaviour of the road is supposed perfectly diffusing with a reflection coefficient equal to πQ_0. The area A_s is the sum of the area of the road under the gonio-reflectometer and of the cover; no apertures are supposed. The value used for ρ is the average of the reflection coefficients of the road and of the internal walls (supposed equal to 0,05).
When the behaviour of the road surface is represented by both CIE C1 and CIE C2 standardized classes, the error on the luminance due to the internal stray light can be evaluated: the maximum is obtained in correspondence with the larger γ angle and is always less than 1% of the luminance produced by the collimated light, only. This value is considered acceptable, as it is smaller than the estimated uncertainty on the calculated road average luminances based on r-table reconstructed form measurements obtained by using the described gonio-riflectometer.

VII. Conclusions

The new gonio-reflectometer presents reduced dimensions, approximately 1m x 1m x 0,8m, allowing its portability and granting the possibility of measuring the reflection property of road paving on site. It avoids the need of picking up samples from the road, a difficult and particularly expensive operation. The system is completely automatic reducing the time consumption. It is shielded from external light, completely, and can operate also in daylight condition. This system could be used to map the status of the road of a municipality, easily, providing the designer of the road light plant the real reflection characteristics of the road under study. These information allow the lighting system has better performance, which fulfils the standards and optimizes the energy cost, thus reducing the light pollution, contemporarily. The expected performances of the measuring system could allow the evaluation of the road reflection characteristics so as the average luminance is calculated with an uncertainty of the order of 5%, which is a good value when the design of a road lighting plant is considered.

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