ENERGEETIKA. ELEKTROTEHNIKA. MÄENDUS D

QUALITY CRITERION OF ROAD LIGHTING MEASUREMENT AND EXPLORING

JELENA ARMAS

Faculty of Power Engineering
Department of Electrical Drives and Power Electronics
TALLINN UNIVERSITY OF TECHNOLOGY

Dissertation was accepted for the defence of the degree of Doctor of Science in Natural and Exact Sciences on August 29, 2008

Supervisor: Professor Juhan Laugis, Dr. Sc.,
Department of Electrical Drives and Power Electronics,
Faculty of Power Engineering, Tallinn University of Technology

Opponents:

Professor Volodimir ANDRIYCHUK, Dr. Sc.,
Ternopil State Ivan Pul´uj Technical University

Professor Endel RISTHEIN, Dr. Sc. Techn.,
Department of Electrical Drives and Power Electronics,
Faculty of Power Engineering, Tallinn University of Technology

Professor Rein LAANEOTS, Dr. Sc.,
Faculty of Mechanical Engineering, Tallinn University of Technology

Defence of Thesis: August 29, 2008

Declaration: Hereby I declare that this doctoral thesis, my original and independent investigation and achievement, submitted for doctoral degree at Tallinn University of Technology, has not been submitted for any degree.

Jelena Armas…………

ABSTRACT

This research focuses on the development of a new method of road lighting measurement, using a luminance measurement camera and camera software. The main objective of the doctoral research is to develop and validate the new method for measurement of road and street lighting according to norms, requirements and European standards.

Emphasis is on the solution of the scientific problems related to enhancing time gain of road lighting measurement.

The thesis consists of six chapters. The first chapter is devoted to the classification of roads and methods of lighting calculation and measurements. The second chapter covers the historical development of measurement methods and requirements of lighting measurements.

In the third chapter theoretical aspects of lighting and human vision are described. Chapter 4 presents a new algorithm for calculation of luminance and illuminance developed by the author. The fifth chapter introduces experimental work related to luminance and illuminance measurements.

In the final chapter advantages of the luminance measurement camera are discussed. Measurements with luminance measurement camera need only a fraction of time for measuring multiple objects in the field of vision as opposed to conventional equipment and these cameras increase the efficiency of work by 30%.

KOKKUVÕTE

Käesolev doktoritöö keskendub uue tänavavalgustuse mõõtmise meetodi arendamisele kasutades kaasaegset kaamerat koos vastava tarkvaraga.

Antud doktoritöö uuringud on pühendatud uue meetodi väljatöötamisele ja selle tähtsuse tõestamisele tee- ja tänavavalgustuse mõõtmiste teostamisel vastavalt kehtivatele normidele, nõuetele ja Euroopa standarditele.

Põhirõhk on teaduslike probleemide lahendamisel, et täiustada tänavavalgustuse mõõtmiste kvaliteeti ning ajalist kasu.

Doktoritöö koosneb kuuest peatükist. Esimene peatükk käsitleb teede ja tänavate klassifikatsiooni ning tänavavalgustuse arvutuse ja mõõtmise meetodite kirjeldamist. Teine peatükk annab ajaloolise ülevaate tänavavalgustuse mõõtmise erinevate meetodite arengust ning mõõtmistele esitatavatest nõudmistest.

Kolmandas peatükis käsitletakse valgustuse teoreetilisi aspekte ja inimeste nägemisvõimet. Neljandas peatükis on esitatud algoritmid heleduse ja valgustiheduse arvutuste kohta. Viies peatükk keskendub eksperimentaalsetele uuringutele heledusest ja valgustihedusest.

Lõpposas vaadeldakse uue mõõtmiskaamera kasutamise eelised, mis võimaldab võita aega ja tõsta efektiivsust 30% võrra.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor, Professor Juhan Laugis, for his guidance, encouragement, and support throughout the course of this work. His extensive knowledge and creative thinking have been an invaluable help.

I gratefully thank Professor Endel Risthein for many enlightening discussions and suggestions. I thank Assoc. Prof. Raivo Teemets, Prof. Tõnu Lehtla, Prof. Valeri Vodovozov, Dr. Argo Rosin, M.Sc. Dmitri Vinnikov, and M.Sc. Madis Lehtla for their valuable contributions as members of my advisory committee.

I also thank the executive director of Minotec DC Toivo Varjas and managing director of Opteema Engineering GmbH Ingo Fischbach, sales manager of Mitaten Finland Leif Riipinen for their help with experiments, valuable assistance and cooperation.

I am grateful to the staff of the Department of Electrical Drives and Power Electronics of Tallinn University of Technology, Ms. Nina Novikova, Ms. Zoja Raud, PhD. Elmo Pettai for their assistance and valuable discussions.

I am very thankful to my family for their support all through my PhD work and understanding that created a favourable atmosphere.

Jelena Armas

Tallinn
August 2008

TABLE OF CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

a	temperature coefficient
A_v	aperture priority mode
AEB	auto exposure bracketing
A/D	analog-to-digital converter
CIE	Commission Internationale de l'Éclairage
CCD	charge coupled device
CMOS	complementary metal oxide semiconductor
$d\Phi_v$	differential luminous flux
DSNU	dark signal non-uniformity
$\bar{E}$	average illuminance (on a road area) horizontal illuminance averaged over a road area. Unit is lux (lx).
E_{min}	minimum illuminance (on a road area) lowest illuminance on a road area. Unit is lux (lx).
E_{hs}	hemispherical illuminance (at a point on a road area) luminous flux on a small hemisphere with a horizontal base. Divided by the surface area of the hemisphere. Unit is lux (lx).
$\bar{E}$	average hemispherical illuminance (on a road area) hemispherical illuminance averaged over a road area. Unit is lux (lx).
E_{sc}	semi-cylindrical illuminance (at a point) total luminous flux falling on a curved surface of a very small semi-cylinder divided by the curved surface area of the semi-cylinder. The direction of the normal on the flat back area inside the semicylinder is to be the direction of orientation of the semi-cylinder. Unit is lux (lx).
$E_{\mathrm{sc,min}}$	minimum semi-cylindrical illuminance (on a plane above a road area) lowest semi-cylindrical illuminance on a plane at a height of 1,5 m above a road area..Unit is lux (lx).
E_{v}	vertical plane illuminance (at a point) illuminance on a vertical plane. Unit is lux (lx).
$E_{\mathrm{v,min}}$	minimum vertical plane illuminance (on a plane above a road area) lowest vertical plane illuminance on a plane at a specified height above the road area
EV	exposure values
$f_2(g)$	directional response
$f_2(u)$	effect from the surrounding field
f_3	linearity error
f_4	error of display unit
f_5	fatigue
f_7	modulated radiation
f_8	polarization
f_{11}	range change
f_{12}	error of focus
f_l	lower frequency limit
f_u	upper frequency limit
Φ_v	luminous flux
$\Phi_\lambda(\lambda)$	spectral radiant power
I	luminous intensity distribution
IR	Infrared

L_{min}	minimum luminance
L_{av}	average luminance
L_{max}	maximum luminance
L_v	luminance
L	average road surface luminance (of a carriageway of a road) luminance of the road surface averaged over the carriageway. Unit is candelas per square meter (cd/m2)
LED	light-emitting diode
LCD	liquid crystal display
m	magnification.
M	manual capture mode
NA	numerical aperture
PRNU	photo response non-uniformity
PC	personal computer
r	radius
π	mathematical constant
ρ	reflectance
SR	surround ratio (of illumination of a carriageway of a road) average illuminance on strips just outside the edges of the carriageway in proportion to the average illuminance on strips just inside the edges
$S(\lambda)$	spectral sensitivity
TI	threshold increment measure of the loss of visibility caused by the disability glare of the luminaries of a road lighting installation
U_l	longitudinal uniformity (of road surface luminance of a carriageway) lowest of the longitudinal uniformities of the driving lanes of the carriageway
U_0	overall uniformity (of road surface luminance, illuminance on a road area or hemispherical illuminance) ratio of the lowest to the average value
$V(\lambda)$	photopic spectral luminous efficiency function
X_e	radiometric quantity
X_v	photometric counterpart
UV	ultraviolet

INTRODUCTION

Accidents at night are more frequent and more serious. Despite lighter traffic, accidents on the roads at night are both more frequent and more serious than at the daytime: nearly 50 percent of fatal accidents occur during the hours of darkness, although night time motoring accounts for only 25 percent of all kilometres driven, as shown in Fig. 1.

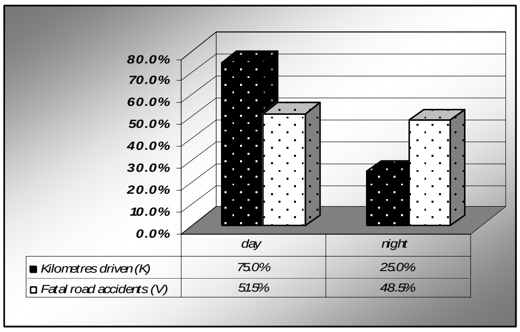


Fig. 1. Kilometres driven (K) and fatal road accidents (V) at the daytime and at night

We rely on our eyes for more than 80 percent of the sensory impressions we register. Thus, poor visual conditions obviously reduce the amount of information that reaches our brain. In road traffic that is extremely dangerous. Street lighting thus contributes to greater safety at night, because it helps or even actually enables us to fill the gaps in the information we receive.

Visual performance is a key factor, however, the root cause remains: the human eye does not perform so well in the dark as in the light. Visual acuity diminishes, distances are harder to gauge, our ability to distinguish colours is reduced, and vision is impaired by glare.

On main roads, luminance and uniformity for the driver are most important. The task of the driver is to locate obstructions in the road ahead. To do this the lighting needs to be bright enough to make small objects with small contrast visible.

Thus, it is luminance that is important to the driver. Thus, main road lighting is based on the calculation of luminance. Illuminance is not a good measure of road lighting as the luminance pattern is dependent on the road surface as well as on the lighting (Fig. 2). The brightness of the area surrounding the road is also important. If it is too bright, then it will raise the driver's adaptation level, if it is too dark, then it will be hard to see pedestrians off the road who may be waiting to cross.

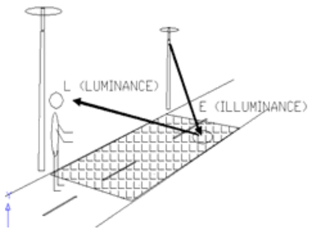


Fig. 2. Luminance and illuminance

Consideration will be given to the following matters related to:

- daytime appearance:
  - choice of a supporting method, for example, columns with or without brackets, suspension wires, or direct mounting on buildings;
  - design and colour of lighting columns;
  - scale and height of lighting columns or other suspension elements in relation to the height of adjacent buildings, trees and other salient objects in the field of view;
  - location of lighting columns in relation to views of scenic value;
  - design, length and tilt of brackets on columns;
  - tilt of luminaires;
  - choice of luminaires.

- night time appearance and comfort:
  - colour appearance of the light;
  - colour rendering of the light;
  - mounting height of the luminaires;
  - light appearance of the luminaires;
  - light appearance of the complete installation;
  - optical guidance by direct light from the luminaires;
  - reduction of light levels in periods [1].

Comfort is again largely controlled by the restriction of glare. As pedestrians move more slowly through an area they do not suffer from disability glare to the same extent. Discomfort glare may be a problem, so the intensities of luminaires near the horizontal must be limited and luminaires should not be mounted at eye height.

Considering the above assumptions, **a completely new measurement and assessment method** developed for luminance and illuminance for the roads and streets **is acceptable for the following reasons**:

1. The proper design and installing of road and street lighting based on more exact measurement data contributes to greater safety of traffic at night.
2. Visual performance is the main aim of road lighting.
3. Requirements of luminance and illuminance for new roads, streets and park lighting measurements are compared according to the standard EN 13201 values.
4. Lighting on minor roads is aimed to satisfy much more the needs of pedestrians. The main objectives of the study of lighting on minor roads to ensure facial recognition, visual orientation and comfort for obstacle detection.
5. In outdoor lighting for obstacle detection by pedestrians it is required that average illuminance be in the range 3 to 10 lx, with a minimum illuminance value of 1 lx.
6. Visual conditions imply the ability to read the road signs and the numbers on the buildings.
7. The design and installing of road lighting installations and equipment can make an essential difference to the appearance of the road and the road environment, at the daytime and at night.
8. This applies not only to the road user, but also to the observer viewing the installation from some distance off the road.
9. There is lack of theoretical and practical knowledge in Estonia in the field of measurement and research related to road luminance and illuminance by the use of a luminance measurement camera in accordance with the European norms and regulations. Light installation companies and service companies need a high level competence to choose the right solutions for road and street lighting. Detailed investigations in this area as well as development of product samples do not only help to gather useful skills and experience, but can improve Estonia's positions on the European and worldwide technology markets.

Thesis Proposal and Objectives

The main objective of the doctoral research, resulting from the problems described above, is **to develop and validate a new method for the measurement of road and street lighting according to the norms, requirements and European standards.**

To achieve this objective, it is required to study and analyze different lighting solutions, using new methods and technologies for lighting measurements (lighting measurement camera with software); to develop new algorithms for luminance and illuminance calculation.

The **main research goals** to be achieved are as follows:

1. Analysis of standards specified for the selection of lighting classes for road lighting;
2. Analysis and systematization of the main criteria and design limitations regarding to road and street lighting according to the lighting class and road category;
3. Comparison of the overall uniformity, longitudinal uniformity factors for different road classes and categories;
4. Evaluation and recommendations of road lighting system solutions (location, components);
5. Realization of the quantitative and qualitative aspects of the luminous environment;
6. Analysis of the geometrical (road width, poles height) and technical elements (luminaire types in terms of flux distribution and visual protection) for lighting calculation;
7. Classification and analysis of software for the calculation of luminance and illuminance;
8. Analysis and comparison of different software packages for lighting calculation;
9. Analysis and comparison of the state of the art of image sensors;
10. Study and evaluation of different measurement instruments;
11. Comparison of luminance and illuminance measurements with the calculated values;
12. Comparison of luminance and illuminance measurements with the standard values;
13. Application of new methods and approaches for luminance and illuminance measurment;
14. Research of software for the optimization of the calculation of luminance and illuminance measurements.

The following **novel scientific approaches and results** are proposed in the thesis:

1. Proposal of a new method of road and street lighting measurement;
2. Proposal of a new algorithm for luminance and illuminance calculation;
3. Analysis and comparison of lighting measurement values with the calculated and standard values;
4. Analysis and comparison of the new proposed measurement method of road and street lighting with the method currently used in Estonia;
5. Analysis and systematization of the recent state of the art trends and technologies regarding to road lighting measurement;
6. Proposals of practical recommendations for the development and use of the new measurement method;
7. Analysis of active standard values and recommendations to increase the minimum standard values;
8. Conclusions and recommendations for further research of the software.

The **direct practical values** of the doctoral work are as follows:

1. Possibility to relate different places of visual and technical data;
2. Time gain of the measurement, i.e. only a fraction of time is required to measure multiple objects in the field of vision in contrast to conventional equipment, to increase the efficiency of work by 30%;
3. All the measuring data achieved at the same time;
4. The luminance picture can be saved and allows a later data iteration;
5. On the basis of the positive results of this research work a business contract will be concluded between the Department of Electrical Drives and Power Electronics of Tallinn University of Technology and Tallinn City Council to conduct research in field of town lighting.

Dissemination of results and publications:

1. The author has over 10 international scientific publications, 5 of those are directly connected to the topic of the doctoral research. The named have all been discussed in conference reports and published in the pre-reviewed international conference proceedings. One paper is published in "12th European Conference on Power Electronics and Applications EPE-2007" and provided for the IEEE Explorer database.
2. The results of the studies were presented and discussed in the City Councils of Tallinn, Estonia, Lithuania, Latvia, Slovenia, Finland, and Denmark.
3. The author will take part in the organization of the seminar "Photographic lighting measurement and colour measurement" in Tallinn.

1. STANDARD DEFINITIONS, CLASSIFICATION OF METHODS FOR CALCULATION AND MEASUREMENT

1.1 Standard definitions

Standard definitions and methods for the calculation of all factors are contained in EN 13201-1 to EN 13201-4: Road Lighting.

Classifications and methods for the calculation are contained in CEN/TR 13201-1:2007: Road lighting - Part 1: Selection of lighting classes, EN 13201-2: Road lighting - Part 2: Performance requirements, EN 13201-3: Road Lighting. Calculation of performance, EN 13201-4: Road Lighting. Methods of measuring lighting performance, DIN 5044 and other relevant industrial standards.

CEN/TR 13201-1:2007: Road lighting - Part 1: Selection of lighting classes - this technical report specifies the lighting classes set out in EN 13201-2 and gives guidelines on the application of these classes. To do this, it includes a system to define an outdoor public traffic area in terms of parameters relevant to lighting. To assist in the application of classes, it suggests a practical relationship between the various series of lighting classes, in terms of comparable or alternative classes. It also gives guidelines on the selection of the relevant area to which the lighting classes from EN 13201-2 and the calculation grids and procedure from EN 13201-3 should be applied [1].

EN 13201-2: Road lighting - Part 2: Performance requirements - this part of the European Standard defines, according to photometric requirements, lighting classes for road lighting aiming at the visual needs of road users, and it considers environmental aspects of road lighting [2].

EN 13201-3: Road Lighting. Calculation of performance - the standard defines and describes the conventions and mathematical procedures to be adopted in calculating the photometric performance of road lighting installations designed in accordance with EN 13201-1 and EN 13201-2 [3].

EN 13201-4: Road Lighting. Methods of measuring lighting performance - this part of the standard specifies the procedures for making photometric and related measurements of road lighting installations [4].

Performance requirements for new street lighting installations are drawn up in the standard EN 13201-2, but in the installed base or stock of street lighting, older equipment does not necessarily meet these relatively new performance requirements, e.g. lighting level, uniformity etc.

The Guideline EN 13201 specifies the selection of lighting classes for road lighting. This guideline considers the lighting classes and provides guidance on the application of these classes. To do this, it includes a system to define an outdoor public traffic area in terms of parameters relevant to lighting. To assist in the application of classes, it suggests a practical relationship between the various series of lighting classes in terms of comparable or alternative classes.

1.2 Lighting class and road category

The standard EN 13201 contains performance requirements in the defined classes (ME1 - ME6, MEW1 - MEW6, CE0 - CE5, S1 - S6, ES1 - ES6, A1 - A6). A lighting class is characterized by a set of photometric requirements aiming at the visual needs of certain road users in certain types of road areas and the environment [2].

These categories with the same lighting levels and more corresponding to the classes used for road lengths are defined hereafter (Table 1 and Fig. 3) [2]:

1. Category ”High >60 km/h” (motorized traffic) “high traffic” with fast motorized traffic use only, having only luminance requirements (cd/m²); also, corresponding to classes ME1 - ME5 or MEW1 - MEW5 for new installations.
2. Category “Moderate 30 km/h - 60 km/h” with motorized traffic, slow moving vehicles, and possibly cyclists and pedestrians with only luminance requirements (cd/m²); also, corresponding to classes ME2 - ME5 or MEW2 - MEW5 for new installations.
3. Category “Low 5 km/h - 30 km/h” for mainly urban and pedestrian areas, with illuminance requirements only (lx), corresponding to classes CE0 - CE5, S1 - S6 and ES, EV and A classes for new installations [2].

Table 1. Classification of the lighting situation

Typical speed or main user type	User types in the same relevant area				Set of situation
	M	S	C	P	
High >60 km/h	*	x	x	x	A1
	*	o	x	x	A2
	*	o	o	o	A3
Moderate 30 km/h - 60 km/h	*	*	o	o	B1
	*	*	*	o	B2
	x	x	*	o	C1
Low 5 km/h - 30 km/h	*	x	x	*	D1
	*	o	o	*	D2
	*	o	*	o	D3
Very low Walking speed	*	*	*	*	D4
	x	x	x	*	E1
	o	o	o	*	E2

M - motorized traffic
S - slow moving
C - cyclist
P - pedestrian
* - yes
O - free for other participants
X - no

Fig. 3 Example of a high traffic, a moderate traffic and a low traffic situation

The ME classes in Table 2 are intended for drivers of motorized vehicles on the traffic routes of medium to high driving speed [2].

Table 2. ME-series of lighting classes

<table>
<tr><th rowspan="2">Class</th><th colspan="3">Luminance of the road surface of the carriageway for the dry road surface condition</th><th rowspan="2">Disability glare
TI %
(maximum)[a]</th><th rowspan="2">Lighting of surroundings
SR
(minimum)[b]</th></tr>
<tr><th>$\overline{L}$ cd/m^2
(minimum maintained)</th><th>U_0 (minimum)</th><th>U_l (minimum)</th></tr>
<tr><td>ME1</td><td>2.0</td><td>0.4</td><td>0.7</td><td>10</td><td>0.5</td></tr>
<tr><td>ME2</td><td>1.5</td><td>0.4</td><td>0.7</td><td>10</td><td>0.5</td></tr>
<tr><td>ME3a</td><td rowspan="3">1.0</td><td rowspan="3">0.4</td><td>0.7</td><td rowspan="3">15</td><td rowspan="3">0.5</td></tr>
<tr><td>ME3b</td><td>0.6</td></tr>
<tr><td>ME3c</td><td>0.5</td></tr>
<tr><td>ME4a</td><td rowspan="2">0.75</td><td rowspan="2">0.4</td><td>0.6</td><td rowspan="2">15</td><td rowspan="2">0.5</td></tr>
<tr><td>ME4b</td><td>0.5</td></tr>
<tr><td>ME5</td><td>0.5</td><td>0.35</td><td>0.4</td><td>15</td><td>0.5</td></tr>
<tr><td>ME6</td><td>0.3</td><td>0.35</td><td>0.4</td><td>15</td><td>no requirement</td></tr>
<tr><td colspan="6">[1] An increase of 5 percentage points in TI can be permitted where low luminance light sources are used.
[2] This criterion may be applied only where there are no traffic areas with their own requirements adjacent to the carriageway.</td></tr>
</table>

Where:

- L [cd/m^2] is the minimum maintained average road surface luminance;
- U_0 is the minimum overall uniformity (of road surface luminance, illuminance on a road area or hemispherical illuminance);
- U_l is the minimum longitudinal uniformity (of road surface luminance);
- TI is the maximum threshold increment: measure of loss of visibility caused by the disability glare of the luminaries of a road lighting installation;
- E [lx] is the minimum maintained average illuminance (on a road area);
- E_{min} is the minimum illuminance (on a road area).

A lighting class is defined by a set of photometric requirements aiming at the visual needs of certain road users in certain types of road areas and the environment:

- overall uniformity of road luminance, U_0 (ABCD surface);
- longitudinal uniformity of road luminance, U_l (OO' line on an observer moving way, within "60÷160 m" zone), Fig. 4.

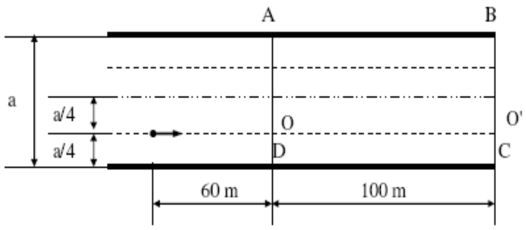


Fig. 4. Determination of U_0 and U_l factors

The standard specifies the quality criteria for road and street lighting, as well as principles of the measuring engineering proof. The standard assumes a two lane street (direction of travel and opposite direction) and prescribes a measuring field (width of one lane x 100 m street length) on the road surface for evaluating the street lighting. This measuring field is 60 m away from the observer's position, with the eye level being 1.5 m (Fig. 5) and the optical axis running parallel to the street level along the middle of the lane [10].

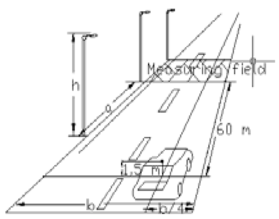


Fig. 5. Measuring fields

Because these idealized capture conditions occur very seldom due to the tectonic conditions, the standard provides for the possibility of utilizing a reduced evaluation surface in the screen measure of the simple distance of the street lighting luminaries. For this, the statistical evaluation field consists of uniformly distributed measuring points "regions", in the raster 6 x 10 (road width x length of the evaluation field).

Visual comfort is certainly related to average illuminance. However, it is also related to the longitudinal uniformity of the lighting (U_l),

$$U_l = L_{min}/L_{max}, \quad (1)$$

where L_{min} is the minimum luminance and L_{max} is the maximum luminance.

This is due to high luminance sources in the visual field. In most installations if the disability glare requirements are met, there is no problem with discomfort glare [12].

As the adaptation state of the driver's vision is set by the average value of the road luminance it is important that the darkest point on the road is controlled or else objects in some parts of the road will not be visible. The measure used to control the uniformity of road luminance is the overall uniformity (U_0),

$$U_0 = L_{min}/L_{av}, \quad (2)$$

where L_{min} is the minimum luminance and L_{av} is the average luminance.

The S classes in Table 3 are intended for pedestrian and pedal cyclists on footway, cycle ways, emergency lanes and other road areas lying separately or along the carriageway of a traffic route and for residential roads, pedestrian streets, parking places [2].

Table 3. S-series of lighting classes

Class	Horizontal illuminance	
	$\bar{E}$ lx [a] (minimum maintained)[a]	E_{min} lx (minimum)
S1	15	5
S2	10	3
S3	7.5	1.5
S4	5	1
S5	3	0.6
S6	2	0.6
S7	performance not determined	performance not determined

[a] To provide for uniformity, the actual value of the maintained average illuminance may not exceed 1.5 times the minimum $\bar{E}$ value indicated for the class.

From this summary of performance requirements the following conclusions can be drawn:

1. There is a large difference between the minimum illuminance (E_{min}) and the minimum maintained illuminance (E) for category **'S'** street lighting;
2. There is a large spread within the minimum maintained luminance (L) for category **'M'** and **'MS'**, while the other parameters e.g. U_o, U_l and TI are rather constant.
3. The primary functional unit of street lighting can be considered as luminance L (cd/m²) for categories **'M'** and **'MS'**, and illuminance E (lx) for category **S'**.
Some examples of the road lighting situation are presented in Table 4.

Table 4. Some examples of the lighting situation

OBJECT	SITUATION
Motorway	A1
Motorwax rest/parking area	D1
Railroad crossing	B1/B2
Bus station	D2
Bus stop waiting area	E1
Shopping area (Pedestrian only)	E1
Shopping area with restricted access for other users	E2
Foothpath along the carriageway	E1
Footpath parallel to the traffic lane	E1
Village main street A3	E1
Roundabout	A/B conflict area
Intersection	A/B conflict area
Rural town to town road without separate footway or cycle path	A3
Local rural road	B1/B2
Local rural road without service road	A2
Parking area	D2
Separate cycle path, along the carriageway	C1
Town to town cycle path in open areas	C1
Urban cycle path connecting areas	C1
Collector road	B1/B2
Express road	A3
Road with limited access	A1
Connecting road in build up area	B1/B2
Urban distribution road	A3
Suburban residential street (footway for pedestrians alongside the carriageway)	D3
Woonerf	D4
30 km/h zone	D4

CIE 144(2001): Road surface and road marking reflection characteristics – this standard is required to calculate the luminance value from illumination conditions for various types of surfaces.

Choice of a road lighting system solution (location, components) depends on how it realizes the quantitative and qualitative aspects of the luminous environment. Geometrical (road width, poles height) and technical elements (luminaire types from flux distribution and visual protection points of view) should also be taken into account.

1.3 Task of lighting engineering

Lighting the area on either side of the road is important in allowing drivers to see pedestrians and other road users who may be about to cross the road. The lighting in a zone of 5 m on either side of the road should be bright enough so that pedestrians can be seen, but not so bright as to change the adaptation state of the driver.

The surround ratio (S_R) is defined as the ratio of the average illuminance on a 5 m strip adjacent to the road compared with the average illuminance on the road; for motorways and other roads where pedestrians are excluded it is not necessary to use the surround ratios [11].

A row of street luminaries can provide useful visual cues to the path of the road by day and night. Care should be taken in installing columns at junctions and on bends so that a false impression of the road layout is not given.

The appropriate quantity and quality of fixed lighting should be designed to provide comfortable visibility for nighttime drivers. Since the purpose of a roadway lighting system is to improve nighttime visual tasks, it is necessary to specify them in terms of quantities that are measurable in the object space. Some of these quantities are given as follows:

- luminance of the object;
- luminance of the background;
- contrast;
- size;
- time;
- temporal frequency characteristics;
- location relative to the line of sight;
- movement in the field of view and non-uniformity of luminance in the object and the background.

Visibility of any target is related to the above variables: additionally, cognitive factors such as attention, expectation and habituation will effect object recognition. The lighting designer directly considers the first four variables listed above. The designers have to assume that both the object (target) and the background luminance are uniformly distributed. The following assumptions will apply:

- increasing luminance increases visibility;
- increasing contrast increases visibility;
- given a dark object on a bright background or a bright object on a dark background improves visibility;

- increasing the visual size of any object increases visibility; given more time to see a target, likelihood of target acquisition becomes better.

The standard EN 13201 recommends that the average luminance of the road surface is in the range 0.3...2 cd/m^2. It depends on road classification. The problem is that the definition of luminance is based on the photopic spectral luminous efficiency function $V(\lambda)$, although it is known that the spectral sensitivity of the eye differs from $V(\lambda)$ in the mesopic luminance range. The spectral sensitivity of the eye in the mesopic luminance range could be defined using a model for mesopic spectral sensitivity.

In lighting engineering, measurements are taken to:

- check lighting proposals;
- check the condition of existing lighting systems to determine whether maintenance is required;
- compare different lighting systems.

Standards and regulations set out stipulations to ensure that the measurement and evaluation methods are standardized.
Important variables are as follows:

- illuminance E, e.g. as horizontal illuminance Eh, vertical lluminance Ev, cylindrical illuminance Ez or semi-cylindrical illuminance Ehz;
- luminance L, e.g. in street lighting, tunnel lighting or interior lighting;
- reflectance ρ, e.g. of ceilings, walls, floors, in workplace interiors and sports halls;
- the reflective properties of road surfaces, e.g. in street and tunnel lighting.

In practice, the variable measured most frequently is illuminance. For this, instruments with a relative spectral sensitivity comparable to that of the human eye $V(\lambda)$ are used. Oblique incident light needs to be measured in line with the cosine law [12].

When preparing photometric procedures, the following has to be established:

- geometric dimensions of the lighting system;
- type of system/nature of interior and activity;
- variables to be measured and location of measuring points,
- general condition of the system, e.g. age, date of last cleaning and last lamp replacement, degree of soiling.

For illuminance measurements, the ground or floor area of the installation in question should be divided into – preferably square – patches of equal size. To avoid that only maximum values are obtained, e.g. directly under luminaires, the measurement grid thus formed should not reflect the modular dimensions of the luminaire arrangement. However, symmetrical features of the lighting system, room or outdoor space can be usefully employed to reduce the number of measurements required.

Measurements are presented in tables. A graphic representation of illuminances in isolux curves is obtained by joining up the points of equal illuminance.

To determine mean illuminance E, individual measurements are put together and divided by the number of points at which measurements are taken.

The uniformity of illuminance is the quotient of the lowest illuminance value denoted E_{min} and the mean illuminance E calculated. Uniformity is the ratio of E_{min} to the highest illuminance value denoted E_{max}.

A record of each measurement should be kept, documenting, for example, not just the values themselves but also the ambient conditions, details of lamps, luminaries and the geometry of the lighting system [13].

1.4 Light measuring technology

Luminance measuring cameras are mounted on high-quality *Charge Coupled Devices* CCD-digital cameras, with each of them being analyzed, calibrated and finally adapted to the light measurement. Thus, the signal values in the image can be converted directly into luminance values.

However, for a number of tasks to be solved in the field of light-measuring technology, it is necessary to determine further characteristics, which can be derived from the luminance data.

For the absolute connection of the out of perspective luminance measuring camera luminance image, it is recommended to provide measuring marks (e.g. signs at a distance of 60 m, 100 m, 160 m from the camera) in the object space or also to utilize already existing marks.

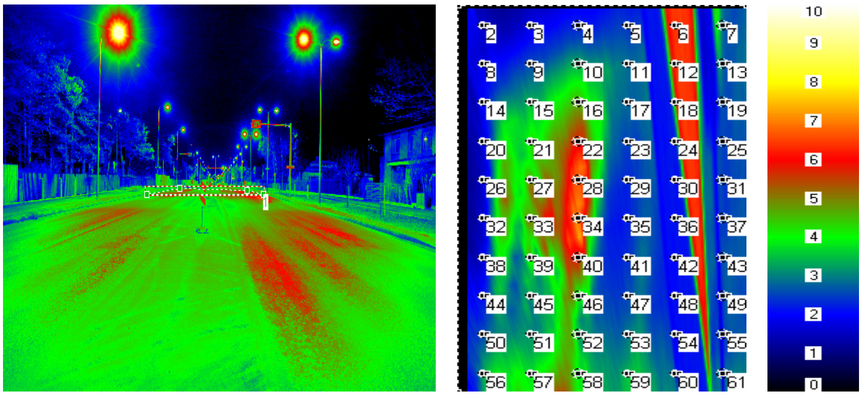


Fig. 6. Polygon (Männiku tee) and grid of points

The image-resolving camera measuring system utilizes the optical mapping of a camera lens. Thus, the geometrical information about the image is ¨projectively distorted“. The camera image evaluation software provides a module for the projective rectification of evaluation regions, which makes it possible to convert metrological information to the x-y-coordinate system. Thus, the direct connection to other measuring and evaluation methods utilizing the point-by-point approach can be realized.

In the luminance image, only the corner points of the measuring field must be indicated (polygon). The projective distortion leads to a rectangular evaluation field (similar to the orthophoto), where a grid of points according to the standard is already fixed (Fig. 6) [28].

2. STATE OF THE ART AND DEVELOPMENT TRENDS

2.1 Historical overview

Progress in a branch of science or engineering is dependent, to a very large extent, on the ability to measure the quantities associated with that subject. Thus, each advance in the measuring technique means a broadening of knowledge.
The measurement of light is called photometry, and a basic instrument employed is known as a photometer. The early photometers depended on visual appraisal as the means of measurement [14].

These are now only rarely used, having been superseded by modern nonvisual “physical” photometers giving higher accuracy and easier use.

The first lighting measurements had been started in the 20th century, in 1900, when the principals of lighting design had been well established during the oil and gas light eras, it was not until the development of the incandescent lamp (c1879) that stage lighting could really flourish as an art form. Now for the first time in history it was possible to provide odourless and controlled lighting. The development of lighting fixtures flourished. The gas; striplight, box flood and footlights were redeveloped using the incandescent lamps [14].

The 'Box Flood' (box flood/scoop/floodlight – the 1900s) is an early type of basic stage lighting fixture. Before the widespread use of electricity and the incandescent lamp, candles, oil lamps and gas were all used for stage lighting. Long ago, some brilliant designer enclosed a typical flame source with a cube type housing, having only one open side. First, the enclosure would have shielded the source from the audience, increasing visibility and visual comfort. Second, the enclosure would have acted as a crude reflector, helping to direct additional reflected light out of the front opening (or aperture).

Soon after the development of the incandescent lamp, the gas floodlight fixture would have been redesigned to incorporate this new technology. The electric box flood was the most basic of all stage lighting fixtures, as all that was required was a metal box, a socket, a power cord and a lamp. No lens or mechanical controls were required.

The illustration above shows a modern day floodlight fixture, using an electric filament lamp. This fixture, known as the 'Scoop', evolved from the simple box flood and provides a soft wide wash of light. Today modern fixtures often incorporate special asymmetrical reflectors, to help provide an even distribution of light on a vertical surface. Some floodlights are also available in multi-cell designs, incorporating 2, 3 or 4 partitioned lamps, each with a different colour filter. Modern floodlights typically come in wattages of 300 - 1000 watts [15].

Adolf Linnebach (LINNEBACH PROJECTOR - c 1900) was the technical director of the Munich Opera in the early 1900s. He developed a simple projector for background and scenic projection. The projector did not use a lens. Instead, it simply cast a shadow of a silhouette cut out, placed in front of the shielded, light source. The result was a simple, effective image projection, with a soft focus. (Bentham).

The modern Linnebach projector uses a slide size of 24x24 or 36x48 (inches). KLIEGL BROTHERS lighting, claims to have introduced the Linneback projector to the American market in 1922.

Footcandle (and Lux) - (a 1900) - It was in the early days of electric lighting that users began to ask how much light they needed. The measurement unit of the footcandle was developed as a measure of **'illumination'**.

Definition - footcandle, fc: The unit of illuminance when the foot is taken as the unit of length. It is the illumination on a surface, one square foot in the area on which there is a uniformly distributed flux of one lumen, or the illumination produced on a surface all points of which are at a distance of one foot from a directionally uniform point source of one candle [14].

The International (metric) unit of illumination is the 'lux'. It is the illumination produced on a surface of one square meter in area at a distance of one meter from a uniform point source.

Lux / Footcandle conversions if you have multiply to obtain:

Footcandles FC = LUX x 0.0929 - Example 1: 500 LUX x 0.0929 = 46.5 FC
Lux LUX = FC x 10.76 - Example 2: 50 FC x 10.76 = 538 LUX

Generally you may multiple FC by 10 to obtain LUX - or, divide LUX by 10 to obtain FC.

The recommended illuminance levels for various activities and tasks are published by the Illuminating Engineering Society. Today we know that it is not just the 'amount' of light that affects visibility. Other factors, such as contrast and glare, are equally important.

Measurements attracting most general interest are:

- illuminance;
- luminance;
- luminous intensity;
- luminous flux,
- contrast,
- colour (appearance and rendering),
- spectral distribution,
- electrical characteristics;
- radiant energy.

In the future work the author will study two of the above: luminance for road and street lighting measurement and illuminance for park street and footpath measurement.

2.2 Photometric methods of measurement

Photometric measurements, in general, make use of the basic laws of photometry. Various types of procedures are designated as follows:

- direct photometry- consisting of simultaneous comparison of a standard lamp and an unknown light source;
- substitution photometry- consisting of the sequential evaluation of the desired photometric characteristics of a standard lamp and an unknown light source in terms of an arbitrary reference;
- relative photometry - consisting of the evaluation of the desired photometric characteristic based upon an assumed lumen output of the test lamp.

A photometer is a device for measuring radian energy in the visible spectrum. Photometers may be grouped according to their function, such as photometers to measure luminous intensity (candlepower), luminous flux, illuminance, luminance, light distribution, light reflectance and transmittance, colour, spectral distribution, and visibility [15].

Illuminance photometers – in recent years, visual photometric methods have largely been supplanted commercially by physical methods; however, visual methods, because of their simplicity, are still used in educational laboratories for demonstrating photometric principles, and the less routine types of photometric measurements.

Luminance photometers – the basic principles discussed earlier relating to photometers for the measurement of illuminance apply equally well to those for the measurement of luminance. Luminance meters consist essentially of a photoreceptor in front of which a direct measure of luminance is produced. Usually an eyepiece is provided such that the user is able to see the general field of view through the instrument [15].

Light from some source, such as the sun, lamp, etc., falls on a surface. The surface reflects some of the light back to the viewer's eye, where it can be used for seeing. The amount of light falling on the surface is the illumination and it is measured in units of lux.

Normally, you measure illumination by putting a light sensor up against the surface and reading an illuminance photometer meter. If there are many light sources, then the meter reads the total illumination coming from all sources.

However, illumination does not specify the amount of light reaching the eye. In short, merely measuring illumination, as is often done, is not enough. We need to measure the amount of light reflected to the eye from

1) the object;
2) the background.

This requires measurement of a different quantity, luminance, which gives the amount of light actually available for vision. The most straightforward measuring procedure is to use a specialized device called a luminance photometer. Place it at the position of the viewer's eyes, aim at the object or surface, which you wish to measure and read the meter in units called candela per meter squared (cd/m^2).

Certainly it is important to read the background, since it is just as important in determining visibility as the target object is positioned, a means of focusing an image of the object of interest onto the photoreceptor (Fig. 7). By suitable optics, therefore, the luminance of a certain size spot when cast onto the receptor will generate an electrical signal, which is dependent upon the object of luminance. This signal can be measured, assuming the necessary calibration has been performed [25].

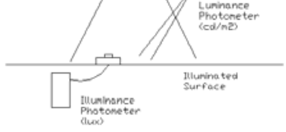


Fig. 7. “Amount of light” measurement

Fig. 8 shows how the illuminance meter is used for measurement. As can be seen, it is difficult to be processed. Therefore one or more illuminace meters are used for multi-point measurement.

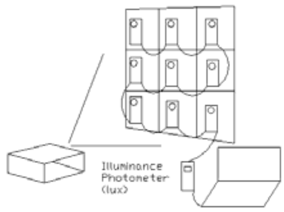


Fig. 8. Multi-point measurement of illuminance

Illuminance meters have a wide range of applications:

- lighting engineering and specifics;
- inspection of light sources at construction sites, government and educational facilities;
- maintenance of lights in factories, offices, and hospitals;
- electrical product manufacturers;
- quality control of light sources at home;
- agricultural and forestry industries.

2.2.1 Requirements for light measurement

Many firms and research laboratories operating in the broad field of optical technologies and research, need specific requirements of light measurement in the following areas:

- LED analysis;
- display measurement,
- spectroradiometry,
- photometry;
- transmission and reflection measurement.

Most of the requirements for light measurement are presented in Table 5, a comprehensive product range of measuring instruments and accessories designed for a wide range of applications. Also, refined turnkey solutions for testing and identifying the optical characteristics of LEDs are given [37].

Table 5. Overview of lighting measuring instruments

Measuring instruments	Turnkey systems	Software	Accessories for LED measurement	General accessories
Spectrometers	LED testers	Lab software	Goniophotometers	Externaloptical probes
Imaging photometers and colorimeters	LED station	Software for production testing	Integrating spheres for luminous flux	Adapters for transmission and reflection
	Display measuring systems	DLLs and drivers	Luminous intensity adapters	Light sources
	Flash lamp measuring systems	Dedicated software	Test sockets (standard and high-power)	Optical fiber

The use of imaging photometers and colorimeters for a fast capture of photometric and colorimetric quantities with spatial resolution has attracted increasing interest. Compared with measuring instruments without spatial resolutions, such as spectrometers, this technology offers the following advantages:

- substantial time-savings with simultaneous capture of a large number of measurements in a single image;
- image-processing functions integrated in the software permit automated methods of analysis, e.g. calculation of homogeneity or contrast.

However, the absolute measuring precision of imaging photometers and colorimeters is not as high as that of spectroradiometers. This is because of the operational principle using a CCD sensor in combination with optical filters, which can only be adapted to the sensitivity of the human eye with a limited precision. Imaging photometers and colorimeters are the instruments of choice to:

- measure luminance and colour distribution of panel graphics and control elements in the automotive industry and avionics;
- measure homogeneity, contrast of flat-panel displays,
- analyze luminous intensity distribution of lamps.

The CCD-technology finds its way into accurate photometric applications of luminance cameras or video photometers lead the world into picture resolved luminance measurements.

2.2.2 Comparison of measuring instruments

Luminance cameras have the following advantages:

- local distribution, it is possible to make a relation between different places of visual and technical data;
- time gain of the measure, it needs only a fraction of time for measuring multiple objects in the field of vision in contrast to conventional equipment;
- constant lighting conditions, all measuring data are achieved at the same time;
- reproducibility, the luminance picture can be saved and allows a later iteration of the data.

Some measurement techniques are presented in Table 6, the last two, i.e., illuminance meter LMT Pocket LUX2 and luminance meter LMT L1009 being used in Estonia.

Table 6. Measuring instruments

Parameters	Lumetrix 300MF	LumiCam 1300	Illuminance Meters LMT POCKET LUX 2	Luminance Meter LMT L 1009
Measurement Capabilities Units	Luminance, illuminance, luminous intensity cd/m2, lux, ftL, cd, user defined	Luminance [cd/m²] Chromaticity [x,y,z] and [u‘,v‘] Dominant Wavelength [nm]	**LMT POCKET LUX 2A**: display range 0.1lx to 199 990 lx **LMT POCKET LUX 2 B**: display range 0.01 lx to 19 999 lx E_z-adapter for the photometer head for cylindrical illuminance E_{sc}-adapter for the photometer head for semi-cylindrical illuminance	display range 0.01 lx to 19 999 lx
Image Resolution	1392 x 1040 (H x V pixels) = approx. 1.45 MPixels	1280 (H) x 1000 (V) effective pixels		
Luminance Range	0.015 to 100,000 cd/m2	0.02 cd/m² to 200,000 cd/m² can be increased by optional density filter	0.01 lx to 19 999 lx	0.01 lx to 19 999 lx
Accuracy	<5% typical, relative to illuminant A calibration standard	± 0.003 for standard illuminant A ± 0.015 for color light		

Today many firms use the lighting measurement camera with the CCD matrix for lighting measurement and research.

The Lighting Laboratory of Helsinki University of Technology, for example, is using the IQCam luminance photometer for research and analysis of luminance measurements. The photometer consists of a CCD based still frame camera and a computer. Controlled by the computer software, the camera captures images from the measurement area with several exposure times and apertures, so that all the luminance values of the area are measured. Simultaneous luminance values of the whole scene are captured in a few seconds. The image consists of 140 000 pixels. The results can be saved as numerical values for later analysis. With the IQCam one can measure and analyze luminance levels and distributions of indoor and outdoor lighting.

The Lighting Laboratory of Helsinki University of Technology has an underground tunnel for an experimental road and street lighting installations at its disposal. The length of the tunnel is 200 m, height 3.5 m and width 5 m. Different lamp types, e.g. HPS, metal halide, LEDs, can be used in the installations.

The tunnel can be used, for example, to study. the effects of lighting conditions on visibility in varied road lighting conditions. As no daylight or other external light enters the tunnel, the weather and lighting conditions remain constant.
The tunnel can also be used for the design of road and street lighting luminaires.

The ProMetric 1400 - Luminance photometer is used by the Lighting Laboratory of Helsinki University of Technology for luminance measurements and analysis in indoor and outdoor lighting. The photometer consists of a peltier cooled CCD based still frame camera and a computer. Simultaneous luminance values of the whole scene are captured in a few seconds. The image consists of 250 000 pixels. The results can be saved as numerical values for later analysis.

The luminance range that can be measured with the ProMetric 1400 is from 0.005 cd/m^2 to 10^{10} cd/m^2. For road lighting measurements a program has been developed at the Lighting Laboratory, which calculates the CIE road lighting parameters from the ProMetric measurement results.

Research areas of the Lighting Laboratory of Helsinki University of Technology:

- road and street lighting;
- vision at low light levels;
- mesopic spectral sensitivity;
- visibility of flashing lights;
- road and street lighting measurements;
- control of road and street lighting;

- LEDs in street lighting.

Properties of the luminance meter as defined by CIE publication 69-1986 [23]:

- deviation of relative spectral responsivity from the V(λ) function - > f_1;
- UV response, IR response -> u, r;
- directional response -> $f_2(g)$;
- effect from the surrounding field -> $f_2(u)$;
- linearity error -> f_3;
- error of display unit -> f_4;
- temperature coefficient -> a;
- fatigue -> f_5;
- modulated radiation -> f_7;
- polarization -> f_8;
- range change -> f_{11};
- error of focus -> f_{12};
- lower/upper frequency limit -> f_l, f_u.

Properties of the video camera system:
- number of pixels (total, effective, output);
- cell size;
- frame rate,
- shutter speed,
- noise;
- dynamic range;
- photo response non-uniformity (PRNU);
- dark signal non-uniformity (DSNU);
- defective pixels;
- optical imaging parameter (MTF, distortion, etc).

Any object that emits light or requires colour testing can be quantified in a matter of seconds with a luminance measurement camera system. For beam pattern evaluations, uniformity of light appearance evaluations, quality control procedures, and display testing of luminance and colour uniformity, the luminance measurement camera system saves time and money.

2.2.3 Methods of outdoor measurements

It is necessary to ensure that illumination of areas such as roads is sufficient such that they comply with relevant safety standards.
Further, some typical methods of outdoor measurements are presented.

Typical methods for such actual outdoor measurements involve laying out a grid pattern (shown in Fig. 9) on the illuminated area and calculating the illumination provided over each area of the grid using a fixed observation point. However, complying with safety standards, such as EN 13201, this is complicated by the requirement that street lighting luminance must be measured in approximately 25 meter intervals along the roadway. EN 13201 sets out detailed requirements covering luminance and glare. With reference to Fig. 9, these requirements are typically satisfied by arranging a grid formation across and along the roadway, a suitable distance away from an observation point, which is generally at least 60 meters away from the grid field. Grid points, spaced apart at D=S/N intervals, are marked onto the roadway at an area under a central street luminaire between opposing street luminaires on the opposite side of the roadway [25], [35].

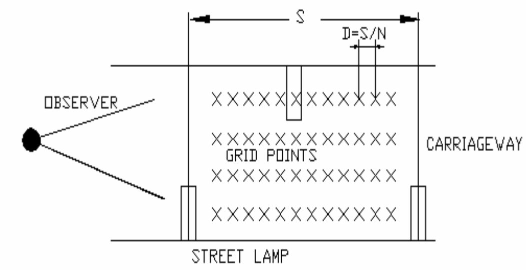


Fig. 9. Grid for measuring street lighting

A measurement of the luminance (candela per mtre squared) is taken manually using a luminance meter (not shown) from the observation point for each grid point. A measurement of illuminance (lux) using an illuminance meter can also be taken at each grid point.

The source of illumination may comprise a road surface, and the method may comprise obtaining at least one substantially absolute measure of the luminance of the road surface and or at least one substantially absolute measure of the illuminance from the road surface. The luminance of the road surface may result from the reflection of light output from one or more street luminaires from the road surface.

The luminous intensity of road and airport runway and approach luminaires are measured in candelas (cd) in a particular direction. Fig. 10 shows ideal isocandela contours as desired for an individual runway and approach luminaire [25], [48].
A graph, such as that shown in Fig. 10, can then be drawn up showing the isolux contours and therefore the illuminance on the roadway beneath the street luminaire.

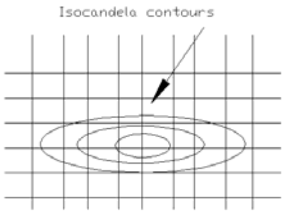


Fig. 10. Isolux graph illustrating contours

Obviously, there are disadvantages associated with measuring luminance and creating isolux contour diagrams in this manner. Firstly, the roadway has to be closed while the measurement takes place. Secondly, the measurements are manpower and time intensive as a grid has to be firstly marked out and then measurements taken for each grid point. There are also various opportunities for errors to be introduced into the measurements.

A less disruptive way of obtaining the required data is to mount sensors on a moving vehicle or trailer (as shown in Fig. 11 and 12) and perform the measurements whilst that vehicle or trailer moves through the illuminated area. Typically, these sensors measure the llumination using single photo-cell devices which are combined with optics to allow both directional and ambient light measurements.

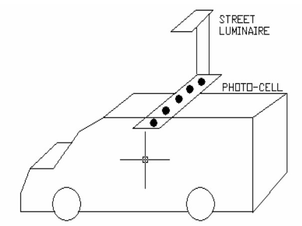


Fig. 11. Schematic diagram: trailer provided with photo sensors for assessing illumination

In Fig. 11, a vehicle with an array of photo-cells mounted on the vehicle's roof is shown. Luminance values are estimated using the row of photocells and relating the values detected to the vehicle's position with respect to the street luminaire. In this method, the location of the luminaire is estimated by assuming that the point of maximum light received at the photo-cells corresponds to the centre of the luminaire estimated by assuming that the point of maximum light received at the photocells corresponds to the centre of the luminaire. This method makes it difficult to find an accurate position of each luminaire with respect to the value measured and, furthermore, there is a possibility that the head of the street luminaire is misaligned with respect to the array of photocells [25].

Another solution for measuring luminous intensity of only airport runway lighting utilizes a vehicle trailer mounted with a grid of photocells, as shown in Fig. 12. The trailer is towed along the runway and over the runway luminaires of interest. The distance along the runway from a reference point is estimated with odometers. The lighting output for each light is estimated as the trailer moves over it. Clearly, the observation angles will vary with distance. To account for this, several columns of cells cover the expected luminaire angles, as shown in Fig. 12.

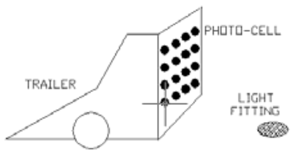


Fig. 12. Schematic diagram for measuring the light output of street luminaires

The photocells in this case are all arranged on a vertical face of the trailer. The distance to the luminaire must be accurately known, so that the constant area of the photocell can be related to the luminous intensity of the luminaire observed by each photocell in a particular direction. The angle of the luminaire with respect to each cell is also important, since the luminous intensity will reduce as the observation angle deviates from zero degrees (where the cell points directly at the luminaire) [25], [48].

However, the relationship between the measured grey level output signals of the pixels of the CCD camera and the actual output of a source is not known. This must be determined, before the camera can be used in situ. This is done using the arrangement shown in Fig. 13. A source of illumination *source* is viewed by a CCD *camera*, and also by a calibrated *luminance meter*. The entire area of the *source* should be enclosed within the acceptance angle of the *luminance meter* (and the *camera*), and this is multiplied by the area which the acceptance angle of the *luminance meter* covers at the distance from the *luminance meter* to the *source*.

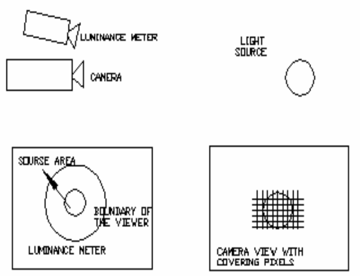


Fig. 13. Block diagram illustrating the calibration of a CCD camera used in the light measurement

With reference to Fig. 14 and using an example of the *luminance meter* having a 0.3 degree acceptance angle, and a distance of 10 m between the *luminance meter* and the *source,* the area that the *luminance meter* views can be calculated according to E_q. (1) below:

Area = $\pi r^2 = \pi(10 \tan) = 0.028798m^2$ (3)

In this example, the total light output from the *source* measured by the *luminance meter*, is therefore calculated as:-

50000 x 0.028798 = 144OcJ (4)

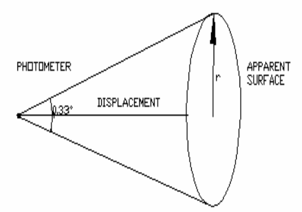


Fig. 14. Geometric diagram showing the calculation of an area

This light output value is used to calculate a camera measurement correction factor for each of the pixels of the camera, which will convert the measured grey level output signal of the pixel to the grey level output signal necessary so that the output signal of the *camera* is concurrent with the light output value measured by the *luminance meter*. Alternatively, the camera measurement correction factor may be used to convert the sum of the measured grey level output signals of the pixels to the grey level output signal necessary so that the output signal of the *camera* is concurrent with the light output value measured by the *luminance meter* [25], [46].

As shown by Fig. 15, at greater distances a single pixel of the array of a CCD camera will cover a far greater viewed area. This makes it difficult to determine the light output of each source of illumination, since only a very small portion of an individual pixel will be covered by the footprint from each source. In addition, the greater distance involved makes it very difficult for the camera to distinguish between one source and the one above or below it in the viewed plane.

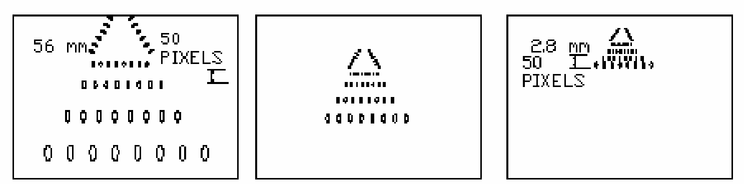


Fig. 15. CCD camera resolution with varying focal length

One or more of the downsides of the apparatus and methods described above could be overcome by using a camera comprising an array of light sensitive pixels, such as a Charge Coupled Device (CCD) camera. However, such cameras present a number of other problems, including the following:

1) The image gathered by the CCD camera can often be illegible due to saturation of the image caused by high levels of brightness.

2) The lens of the camera typically distorts the image in such a way that the actual position of the luminaire may be different from the apparent position of the luminaire through the lens.
3) The CCD camera is typically unable to interpret the relationship between the brightness measured by a pixel and the actual brightness of the particular type of luminaire viewed.
4) Typical CCD cameras are unable to track the movement of a particular light across the image with time; this is necessary to obtain a correct overall measurement for each individual luminaire.

According to the first aspect, a light measurement method is provided that comprises the following: determination of one or more correction factors for at least one image capture device; use of the image capture device to receive light output from at least one source of illumination; obtaining an output from the image capture device which corresponds to the light output of the source of illumination; and applying the or each correction factor to the output of the image capture device to obtain one or more substantially absolute measures of the light output of the source of illumination.

The image capture device may be moving with respect to the source of illumination, while being used to receive light output from the source of illumination.

The image capture device may be a camera. The camera may be a charge coupled device (CCD) camera. Obtaining an output from the CCD camera which corresponds to the light output of the source of illumination may comprise obtaining one or more grey level output signals from one or more CCD pixels of the CCD camera. The camera may be a complementary metal oxide semiconductor (CMOS) camera.

2.3 CCD and CMOS image sensors of a measuring cameras

Like all technical devices, a luminance and colour measuring cameras presents some properties, which do not correspond with ideal models. These differences can be grouped into systematic and stochastic components. Any deviations of the measuring values from the ideal behaviour, which are determined, can be recorded and corrected. Whether the systematic remaining deviations after the correction are significant or not, however, will depend on the technological prerequisites, the available calibration means as well as on the care taken during calibration. The stochastic components include signal-dependent and signal-independent noise.

Luminance measuring cameras are mounted on high-quality *Charge Coupled Devices* CCD or *Complimentary Metal Oxide Semiconductor* CMOS.

There are two primary types of electronic image sensors, charge coupled devices (CCDs) and complimentary metal oxide semiconductor (CMOS) sensors [26].

CCD and CMOS image sensors are two different technologies for capturing images digitally. Each has unique strengths and weaknesses giving advantages in different applications. Neither is categorically superior to the other, although vendors selling only one technology have usually claimed otherwise. In the last five years much has changed with both technologies, and many projections regarding the demise or ascendance of either have been proved false. The current situation and outlook for both technologies is vibrant, but a new framework exists for considering the relative strengths and opportunities of CCD and CMOS imagers.

Both types of imagers convert light into electric charge and process it into electronic signals. In a CCD sensor, every pixel's charge is transferred through a very limited number of output nodes (often just one) to be converted to voltage, buffered, and sent off-chip as an analog signal. All of the pixel can be devoted to light capture, and the output's uniformity (a key factor in image quality) is high. In a CMOS sensor, each pixel has its own charge-to-voltage conversion, and the sensor often also includes amplifiers, noise-correction, and digitization circuits, so that the chip outputs digital bits [48].

These other functions increase the design complexity and reduce the area available for light capture. With each pixel doing its own conversion, uniformity is lower. But the chip can be built to require less off-chip circuitry for basic operation (Table 7).

Table 7. Feature comparison

	CCD	CMOS
Signal out of pixel	Electron packet	Voltage
Signal out of chip	Voltage (analog)	Bits (digital)
Signal out of camera	Bits (digital)	Bits (digital)
Fill factor	High	Moderate
Amplifier mismatch	N/A	Moderate
System noise	Low	Moderate
System complexity	High	Low
Sensor complexity	Low	High
Camera components	Sensor + multiple support chips + lens	Sensor + lens possible, but additional support chips common
Relative system cost	Depends on application	Depends on application

CCDs and CMOS imagers were both invented in the late 1960s and 1970s, but CCDs became dominant, primarily because they gave far superior images with the fabrication technology available. CMOS image sensors required more uniformity and smaller features than silicon wafer foundries could deliver at the time [26].

Not until the 1990s did lithography develop to the point that designers could begin making a case for CMOS imagers again. Renewed interest in CMOS was based on expectations of lowered power consumption, camera on a chip integration, and lowered fabrication costs from the reuse of mainstream logic and memory device fabrication. While all of these benefits are possible in theory, achieving them in practice while simultaneously delivering high image quality has taken far more time, money, and process adaptation than original projections suggested.

Both CCDs and CMOS imagers can offer excellent imaging performance when designed properly. CCDs have traditionally provided the performance benchmarks in the photographic, scientific, and industrial applications that demand the highest image quality (as measured in quantum efficiency and noise) at the expense of system size. CMOS imagers offer more integration (more functions on the chip), lower power dissipation (at the chip level), and the possibility of smaller system size, but they have often required tradeoffs between image quality and device cost. Today there is no clear line dividing the types of applications each can serve. CMOS designers have devoted intense effort to achieving high image quality, while CCD designers have lowered their power requirements and pixel sizes. As a result, CCDs can be found in low cost low power cellphone cameras and CMOS sensors in high performance professional and industrial cameras, directly contradicting the early stereotypes. It is worth noting that the producers succeeding with "crossovers" have almost always been established players with years of deep experience in both technologies [26],[45].

Costs are similar at the chip level. Early CMOS proponents claimed CMOS imagers would be much cheaper because they could be produced on the same high-volume wafer processing lines as mainstream logic or memory chips. This has not been the case. The accommodations required for good imaging performance have required CMOS designers to iteratively develop specialized, optimized, lower volume mixed signal fabrication processes very much like those used for CCDs. Proving out these processes at successively smaller lithography nodes (0.35 um, 0.25 um, 0.18 um.) has been slow and expensive; those with a captive foundry have an advantage because they can better maintain the attention of the process engineers.

CMOS cameras may require fewer components and less power, but they still generally require companion chips to optimize image quality, increasing cost and reducing the advantage they gain from lower power consumption. CCD devices are less complex than CMOS, so they cost less to design. CCD fabrication processes also tend to be more mature and optimized; in general, it will cost less (in both design and fabrication) to yield a CCD than a CMOS imager for a specific high-performance application. However, wafer size can be a dominating influence on the device cost; the larger the wafer, the more devices it can yield, and the lower the cost per device. 200 mm is fairly common for third-party CMOS foundries while third-party CCD foundries tend to offer 150 mm. Captive foundries use 150 mm, 200 mm, and 300 mm production for both CCD and CMOS (Table 8).

Table 8. Performance comparison

	CCD	CMOS
Responsivity	Moderate	Slightly better
Dynamic Range	High	Moderate
Uniformity	High	Low to moderate
Uniform Shuttering	Fast, common	Poor
Uniformity	High	Low to moderate
Speed	Moderate to high	Higher
Windowing	Limited	Extensive
Antiblooming	High to none	High
Biasing and clocking	Multiple, higher voltage	Single, low-voltage

While cost advantages have been difficult to realize and on-chip integration has been slow to arrive, speed is one area where CMOS imagers can demonstrate considerable strength because of the relative ease of parallel output structures. This gives them great potential in industrial applications.

CCDs and CMOS will remain complementary. The choice continues to depend on the application and the vendor more than the technology [26], [39].

2.4 Development of luminance and illuminance measurements

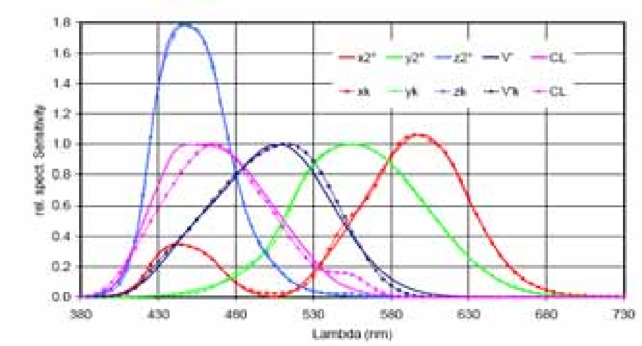
In general, light measurement with physical instruments is useful only if the instruments indicate reliably how the eye would react to certain stimulus. In other words, such an instrument should be sensitive to the spectral power distribution of light in the same way as the eye.

The luminance $L\ (x,y,\vartheta,\varphi)$ is a position-dependent (differential) measuring quantity, thus requiring to be imaged onto the sensor, in the case of sensors measuring point-by-point the imaging of the given measuring spot, in the case of image-resolving luminance meters the imaging of the corresponding scene onto the image sensor (CCD-matrix) [27].

To realize measuring systems of this kind, it is necessary to have exact knowledge of the physical connections between charge generation, transport and conversion, as well as of other characteristic features of the CCD-matrix used (temperature profile, darkness profile). Essential connections and dependences and their parameters must be recorded and corrected.

If the system is used to measure luminances or also tristimulus values, then the spectral sensitivity of the whole system must be adapted to the $V(\lambda)$ - function filter or also a set of filters is used for each camera.

The CCD-matrix, a radiation-sensitive sensor, converts the incident radiant flux into signal charges according to their spectral sensitivity $S(\lambda)$. If the system is to perform photometric measurements, i.e. luminance measurements, the spectral sensitivity of the overall system must be $V(\lambda)$ or also to the colour-matching functions x(λ) y(λ) z(λ). The use of the filter or also the combination of the measuring values of the set of filters, together with the spectral sensitivity of the respective sensor and the spectral transmission of the object, make sure that the measuring system is properly adapted to the standard sensitivity mentioned above. In order to ensure this, a filter $F\ (\lambda)$ is used for each camera which – together with the spectral sensitivity of the respective CCD-matrix and the spectral transmission of the lens, provides for the sensitivity of the human eye complying with standards, namely $V(\lambda)$ [32].



Lambda (nm)

Fig. 16 Relative spectral sensitivity of the camera compared with standard sensitivities

By means of the measuring system of the camera, which realizes the relative spectral sensitivities shown in Fig. 16, it is possible to determine in an image resolved way luminances in the photopic and in the scotopic range (V(λ),V'(λ)), circadian quantities (C(λ) [27]) and tristimulus values (X,Y,Z(λ) [28].

2.5 Technical parameters: calibration and resolution

The technical parameters of each luminance measurement camera are laid down in a calibration. Essential features of a measuring device are the data resolution and the reachable dynamic range. In the case of single shots, the resolution is determined by the data width of the A/D converter and by the signal to noise ratio. The resolution of the measuring data can be enhanced via averaging over neighbouring pixels on the matrix (binning), or by means of the software (macropixels), or also by means of several images successively recorded and averaged (multiple measurement) to about

$$n = n_0 + \frac{ldN}{N}, \qquad (5)$$

where N is the number of averaged pixels or pictures, n is the result of resolution bits and n_0 is the basic resolution.

When using the measuring camera for luminance or also colour measurements or for determining derived photometric quantities, not only the properties of the measuring system itself (technical parameters) but also a variety of other influences are decisive in order to obtain sufficiently exact measuring results. As it is true for all kinds of measuring systems, an improper handling may lead to severe misinterpretations. Therefore, it is urgently recommended to critically evaluate each measuring result. Besides the improper handling of the measuring system, with the imaging of the scene (blurred mapping, measurement of too small structures) having a particularly strong influence, also the layout of the scene is very important. Thus, the measuring data can be distorted, for example, by scattered light (whose magnitude is often underestimated) or by some instabilities such as the flickering of lamps, and may therefore supply only little or no information at all about the photometric parameters of the device, the whole installation or the scene [56].

Radiometry is the science of measuring light, whether visible to the human eye or not. Photometry, a subset of radiometry, is defined in the same way except that the measurements refer to light as detected by the human eye.

In order to determine the optimum camera set up for most applications it is useful to calculate the expected output from a camera given knowledge of the lighting conditions and the nature of the objects to be imaged. If the scene contains many different objects with different colours and reflective properties it is very difficult to calculate the nature of the reflected light. The amount of light falling on the scene is known as the irradiance and is expressed as a power density.

Some of this light will be reflected by the surface into one or many different directions. The light reflected from the surface and received at a point some distance away from it is known as the radiance, the power per unit area, per unit solid angle. A scene containing many different objects is difficult to characterize when their reflectance varies widely, particularly when some highlights in the scene are brighter than the rest.

In order to accommodate the wide latitude of a complex scene it is possible to use an average value for the reflection. In this way, the radiance is assumed to be equivalent to that which would have resulted from a "standard" surface.

The complex calculations required to determine the reflected light are difficult and therefore, at best provide only a rough guide to the camera response. Hence it is often easier to measure the average visible light intensity reflected from an object with a simple light meter, bearing in mind that the spectrum will depend on the nature of the illumination and the object. Nevertheless, if the irradiance of the camera is known, then the output of a camera system can be calculated by integrating the known spectral response function of the camera with the spectral illumination curve at the sensor.

The light reflected from the scene is collected by the camera and focused onto the CCD sensor by the lens. In addition to providing a sharply focused image the lens also increases the light intensity. Strictly speaking, the lens will absorb some of the light and will itself have a spectral absorption response, but for the purpose of estimation this can be ignored. The amount of light collected by the lens will also depend on its diameter.

As a result the effective light gathering power of the lens is related to its f-number, the ratio of its focal length to diameter, or more accurately, directly proportional to the numerical aperture (NA), the reciprocal of $2 \times f - number$. Hence, it can be shown that the irradiance of the CCD sensor is:

$$Irradiance = p \times Object\ Radiance \times \frac{NA}{(m+1)^2}, \tag{6}$$

where *m* is a magnification.

For the technical measuring system, the following effects, among other things, must be corrected or even avoided: dark signal, non-linearity, shielding of the lens (shading), blooming, and smear und blemish pixels [27].

In the following, the scattered light is considered as an example: each imaging system produces a smaller or bigger portion of scattered or pseudolight. The imaging system is made up of lenses or mirrors, which do not only present ideal functions (lenses – refraction during the passage of light through the system; mirrors - reflection), but also a non-ideal behavior.

Glassier transitions do not only refract the light, but also reflect it (about 4%); mirrors do not only reflect the light in a directed way but also diffusely. Light can be scattered on lens mountings and on diaphragms.

Thus, light will be transmitted from the object not only to those places resulting from the geometrical optical system, but also to a number of other places. Furthermore, the sensor itself has a finite reflectivity (silicon 30 ...65 %). This means that the light imaged onto the sensor is reflected to a large extent, thus “wandering around the lens”. All these effects produce a more or less strong "carpet of scattered light" [59].

Some problems associated with the camera are

- timing problems (integration time : 0.01 msec - 1 sec);
- dark current (resp. drift of dark current), depends on the temperature, position;
- fixed aperture/ focus versus variable aperture/ focus ;
- image compression;
- straylight;
- moire-effects;
- data acquisition, manipulation, and evaluation done by a computer.

There is always a mathematical transformation between the luminance value and the pixel value, typically:

- the ideal condition
  luminance(x,y,t) = pxl (x,y,t) * calibration

- the real condition
  luminance(x,y,t) = (pxl (x,y,t) - dark(x,y) - dark(t)) * calibration * shading (x,y) * nonlinearity (pxl)

This entails two important measuring problems:

- Due to scattered light, largely illuminated objects present a slightly higher measuring value (depending on the illumination of the object field on the whole).
- In dark regions, scattered light is additionally measured, i.e., the contrasts measured are always smaller than the actual contrasts (also depending on the illumination of the object field on the whole). This is important particularly when evaluating scenes with small dark structures on a large bright background.

3. THEORETICAL ASPECTS

3.1 Background

Light, or the visible part of the electromagnetic radiation spectrum, is the medium through which human beings receive a major portion of environmental information. Evolution has optimized the human eye into a highly sophisticated sensor for electromagnetic radiation. Joint performance between the human eye and visual cortex, a large part of the human brain, dwarfs recent technical and scientific developments in image processing and pattern recognition. In fact, a major part of the information flow from external stimuli to our brain is transferred visually. Photometry deals with the measurement of this visible light energy.

However, optical radiant energy not only encompasses visible 'light' but radiation invisible to the human eye as well. The term ‘optical’ is used because this radiation follows the laws of geometrical optics.

Radiometry deals with the measurement of all optical radiation inclusive of the visible portion of this radiant energy [29].

Thorough knowledge of the physical nature of light and light perception provides the foundation for a comprehensive understanding of optical measurement techniques. Yet, from a practical point of view there is little necessity to fully understand formation and propagation of light as an electromagnetic wave as long as the reader accepts wavelength as the most important parameter describing the quality of light. The human eye perceives light with different wavelengths as different colours (Fig. 17.), as long as the variation of wavelength is limited to the range between 400 nm and 800 nm (1 nm = 1 nanometer = 10^{-9} m). Outside this range, our eye is insensitive to electromagnetic radiation and thus we have no perception of ultraviolet (UV, below 400 nm) and infrared (IR, above 800 nm) radiation.

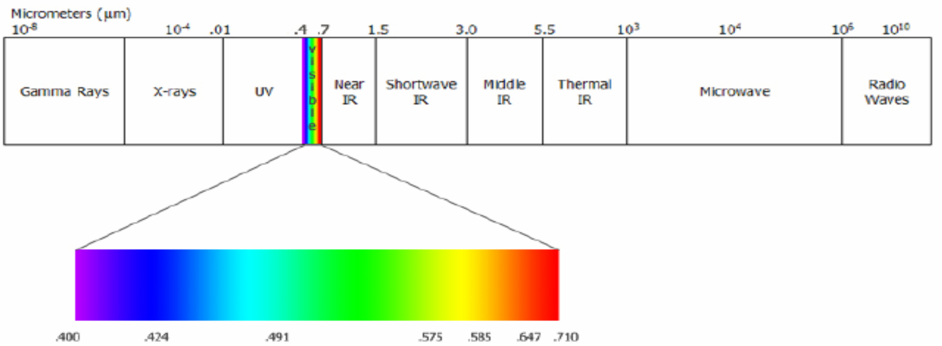


Fig. 17. The visible spectrum (wavelength in micrometers)

The sensitivity of the human eye to light of certain intensity varies strongly over the wavelength range between 380 and 800 nm. Under daylight conditions, the average normal sighted human eye is most sensitive at a wavelength of 555 nm, resulting in the fact that green light at this wavelength produces the impression of highest "brightness" when compared to light at other wavelengths. The spectral sensitivity function of the average human eye under daylight conditions (photopic vision) is defined by the *CIE spectral luminous efficiency function V(λ).* According to the Commission Internationale de l'Éclairage (International Commission on Illumination, CIE), the lower luminance limit of the mesopic luminance range is about 0.001 cd/m² and the upper limit is 'at least several cd/m² [22]. Only in very rare cases, the spectral sensitivity of the human eye under dark adapted conditions (scotopic vision), defined by the spectral luminous efficiency function *V'(λ*), becomes technically relevant. By convention, these sensitivity functions are normalized to a value of 1 in their maximum.

As an example, the photopic sensitivity of the human eye to monochromatic light at 490 nm amounts to 20% of its sensitivity at 555 nm. As a consequence, when a source of monochromatic light at 490 nm emits five times as much power (expressed in watts) than an otherwise identical source of monochromatic light at 555 nm, both sources produce the impression of same "brightness" to the human eye.

3.2 *Mesopic* vision

There are two types of receptors on the retina of the eye: rods and cones. The rods operate at low light levels, the cones operate at high light levels, and both operate over a range at intermediate light levels. Rod vision does not provide colour response or high visual acuity. In fact, there is no rod vision along the line of sight; in looking for a very faint signal light on a dark night, one must look about 15 degrees to the side of it. The cones are responsible for colour vision and the high acuity necessary for reading and seeing small details. Visual performance is best in daylight, when the eye's colour-sensitive cone receptors are activated: colours are easily distinguished, objects and details clearly made out. In darkness, different receptors are active: rods, which are fairly insensitive to colour but highly sensitive to brightness. In the transitional stage of twilight, both receptor groups are active (Fig. 18) [16].

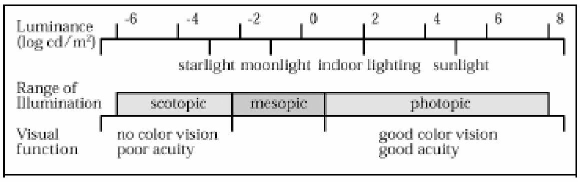


Fig. 18. Approximate ranges for rod and cone operation

Since these depend on the luminance ("brightness") in the field of view rather than on illuminance (footcandles or lux), typical lighting conditions at which these luminances occur are indicated across the top of the chart. Rod vision is known as *scotopic* vision, cone vision is known as *photopic* vision, and the region where both rods and cones contribute to vision is called *mesopic* vision. Light (lumens) is radiant power in watts weighted at each wavelength by a luminous efficiency value, i.e., by the eye's brightness response to power at that wavelength. We can derive the lumen value of a light by this spectral weighting process using the photopic or the scotopic response function [30].

Fig. 19 shows the standardized spectral weighting functions for photopic and scotopic lumens. The change in response functions is known as the *Purkinje shift*.

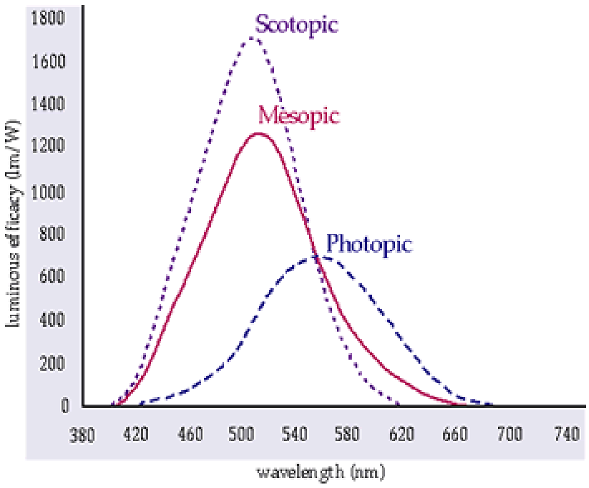


Fig. 19. Standard spectral eye-sensitivity curves for photopic and scotopic vision according to CIE

In the mesopic region, as the light level decreases from photopic to scotopic vision, the spectral response gradually changes from the photopic to the scotopic curve. There is a continuous range of mesopic curves changing in both shape and maximum sensitivity, and the appropriate curve depends on such factors as the light level and the distribution of light in the field of view. A review of the issues and of various methods for estimating mesopic vision can be found in *Mesopic*

Photometry: History, Special Problems and Practical Solutions CIE Publication [21].

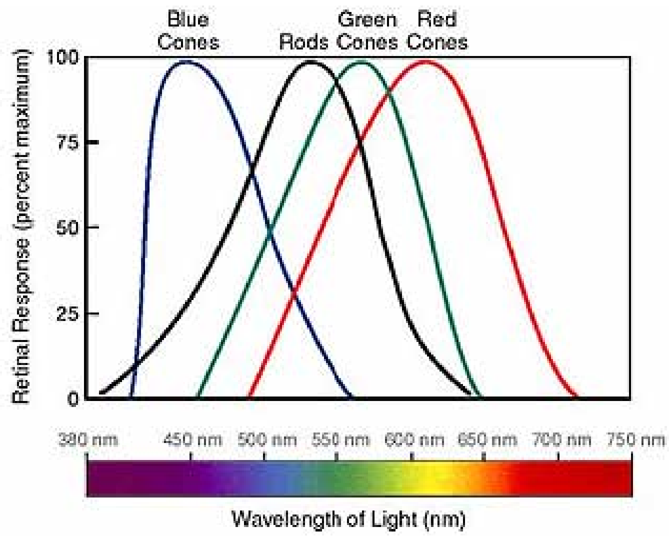


Fig. 20. Relative spectral sensitivity of all four types of the human eye's light receptors

The three different kinds of cones differ in their spectral sensitivity to electromagnetic radiation, which is shown in Fig. 20 for the average normal sighted human eye. If monochromatic radiation irradiates the eye, as it is the case with spectral decomposition of white light, the wavelength determines which types of cones are excited. For instance, monochromatic light at 680 nm exclusively excites one type of cones, whereas the two other types are insensitive at this wavelength. The brain interprets signals from only this type of cones - in the absence of a signal from the other cones - as the colour ¨red“. Therefore, these cones are called ¨red cones“. Similarly, the two other types of cones are called ¨blue cones“ and "green cones" [16], [29].

3.3 Luminous flux Φ_v

Luminous flux Φ_v is the basic photometric quantity and describes the total amount of electromagnetic radiation emitted by a source, spectrally weighted with the human eye's spectral luminous efficiency function $V(\lambda)$. Luminous flux is the photometric counterpart to radiant power. The unit of luminous flux is lumen (lm), and at 555 nm, where the human eye has its maximum sensitivity, a radiant power of 1 W corresponds to a luminous flux of 683 lm. In other words, a monochromatic source emitting 1 W at 555 nm has a luminous flux of exactly 683 lm. The value of 683 lm / W is abbreviated by the symbol K_m (the value of K_m = 683 lm/W is given for photopic vision. For scotopic vision, K_m=1700 lm/W has to be used). However, a monochromatic light source emitting the same radiant power at 650 nm, where the human eye is far less sensitive and $V(\lambda) = 0.107$, has a luminous flux of 683 lm 0.107 = 73.1 lm [1].

3.4 Luminance L_v

Luminance L_v describes the measurable photometric brightness of a certain location on a reflecting or emitting surface when viewed from a certain direction. It describes the luminous flux emitted or reflected from a certain location on an emitting or reflecting surface in a particular direction (the CIE definition of luminance is more general. Within the frame of this tutorial, the most relevant application of luminance describing the spatial emission characteristics of a source is discussed) [16].

In detail, the (differential) luminous flux $d\Phi_v$ emitted by a (differential) surface element dA in the direction of the (differential) solid angle element $d\Omega$ is given by

$$d\Phi_v = L_v \cos(\theta)\, dA\, d\Omega \qquad (7)$$

with Θ denoting the angle between the direction of the solid angle element $d\Omega$ and the normal of the emitting or reflecting surface element dA.

The unit of luminance is

$1 \text{ lm m}^{-2} \text{ sr}^{-1} = 1 \text{ cd m}^{-2}$

3.5 Illuminance E_v

Illuminance E_v describes the luminous flux per area impinging upon a certain location of an irradiated surface. In detail, the (differential) luminous flux $d\Phi_v$ upon the (differential) surface element dA is given by

$$d\Phi_v = E_v\, dA \qquad (8)$$

Generally, the surface element can be oriented at any angle towards the direction of the beam. Similar to the respective relation for irradiance, illuminance E_v upon a surface with arbitrary orientation is related to illuminance $E_{v,normal}$ upon a surface perpendicular to the beam by

$$E_v = E_{v,normal} \cos(\vartheta) \qquad (9)$$

with ϑ denoting the angle between the beam and the surface's normal [30].

The unit of illuminance is lux (lx), and
1 lx = 1 lm m^{-20}

3.6 Conversion between radiometric and photometric quantities

Monochromatic radiation: In the case of monochromatic radiation at a certain wavelength λ, a radiometric quantity X_e is simply transformed to its photometric counterpart X_v by multiplication with the respective spectral luminous efficiency $V(\lambda)$ and by the factor K_m = 683 lm / W. Thus,

$$X_v = X_e \ V(\lambda) \ 683 \text{ lm / W} \qquad (10)$$

with X denoting one of the quantities Φ, I, L, or E.

Polychromatic radiation: If a source emits polychromatic light described by the spectral radiant power $\Phi_\lambda(\lambda)$, its luminous flux can be calculated by spectral weighting of $\Phi_\lambda(\lambda)$ with the human eye's spectral luminous efficiency function $V(\lambda)$, integration over wavelength and multiplication with with K_m = 683 lm / W, so

$$\Phi v = Km\int \Phi(\lambda)V(\lambda)d\lambda \qquad (11)$$

In general, a photometric quantity X_v is calculated from its spectral radiometric counterpart $X_\lambda(\lambda)$ by the relation

$$Xv = Km\int X\lambda(\lambda)V(\lambda)d\lambda \qquad (12)$$

with X denoting one of the quantities Φ, I, L, or E.

Based on the fact that spectral decomposition of white light produces the perception of different colours, it can be deduced that colour perception is closely connected to the wavelength of light. As an example, light with a wavelength of 650 nm wavelength is perceived as ¨red“ and light with a wavelength of 550 nm is perceived as ¨green“. However, there are colours, such as purple, which cannot be directly related to a certain wavelength and therefore do not occur in the spectral decomposition of white light [14], [28].

4. DEVELOPMENT OF A NEW ALGORITHM FOR LUMINANCE AND ILLUMINANCE CALCULATION

In general, the luminance and the colour values can be directly obtained from the luminance and colour images, respectively. For doing this, the LMK2000 software offers numerous functions, which permit the user to evaluate and display luminance sectional views, histograms and simple statistics (means value, variance, minimum, maximum), like the luminances are analyzed, as a function of the luminance or the environment.

4.1 Luminance analysis

However, for a number of tasks to be solved in the field of light measuring technology, it is necessary to determine further characteristics, which can be derived from the luminance data.

A luminance analysis depends on a photometrical and geometrical calibrated CCD camera.

The analysis needs a personal computer (PC), which is equipped with an image processing board and the necessary software. This device can measure luminances with a very high spatial resolution and with a large solid angle.

Together with the distortion correction of the camera, a target luminance image is composed of a multitude of high-resolution images taken at various camera orientations (Fig. 21).

The camera and its CCD chip are optimized for accurate measuring luminances [26], [30]. This includes the spectral $V(\lambda)$-correction, shading correction, compensation of dark current and temperature-drift, as well as the absolute calibration of the system.

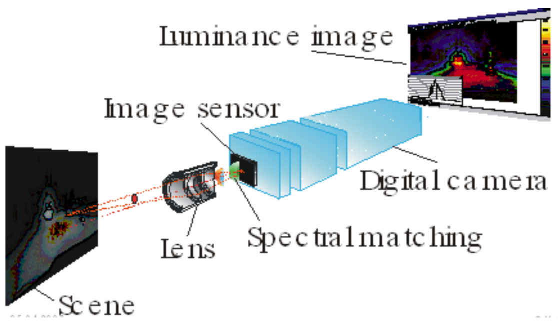


Fig. 21. Principle of the luminance analyzer

The composite high resolution luminance image is the starting point of the real luminance analysis. Through spatial calibration pixel coordinates are directly related to polar angles subtended by the pixel relative to a defined line of sight, some of optical format explained in Table 9.

Table 9. Optical format

Format	Array format		Pixel
	horizontal	vertical	
QCIF - Quarter Common Intermediate Format	176	144	25300
QVGA - Quarter Video Graphics Array	320	240	76800
CIF - Common Intermediate Format	352	288	101400
VGA - Video Graphics Array	640	480	307200
SVGA - Super Video Graphics Array	1024	768	786400
SXGA	1032	1288	1329200 (1 megapixel)
Digital HDTV - High-Definition TV	1280	720	921600 (1 megapixel)

Therefore, all luminance and geometric properties of a scene can be calculated. For instance, the direct and indirect luminance at the camera position in any plane can be determined, as well as average luminances and luminance ratios.

The next step in the luminance analysis is the classification of the image. For each part of the image a decision is made whether it belongs to a luminaire or the background, to any window or wall or similar groupings, depending on the task to be performed.

The luminance analyzer was designed to measure glare indices, thus it is important to know if a point is part of a light source or not. The criteria are used for a luminance threshold. If the luminance of an object area is higher than the threshold luminance, then it is part of a light source, otherwise it belongs to the background.

After the classification, a numerical list of all contiguous light source areas was generated. Such a contiguous area is called a "luminance object". For each luminance object, a number of values can be calculated based on the measured luminance and geometry, for instance:

- average luminance;
- angles relating the source location to the line of sight;
- position index;
- solid angle of the source;
- illuminance on the observer's eye (glare illuminance) caused by this light source;
- all of the values are required to calculate glare values.

In general, the luminance and the colour values can be directly obtained from the luminance and colour images, respectively. For doing this, the lighting measurement camera software offers numerous functions, which permit the user to evaluate and display luminance sectional views, histograms and simple statistics (mean value, variance, minimum, maximum) to analyze the luminance's, as a function of the luminance or the environment.

4.2 Digital image capturing and processing

The dynamic range, which can be recorded by means of a luminance measuring camera, can be improved by a HighDyn-measurement, in case of which the scene is captured several times at different integration times. Then, the measuring values are obtained from the images with the best signal to noise ratio and converted into a common luminance image.
The software of the Techno Team mobile advance LMK2000 (Canon 350D) device will be installed in the directory specified by the user. After that, the installation and the working directories are identical as per default in the automatically installed links. These links are used when the program is started up by double-clicking on an icon on the desktop or by selecting a menu item in the start-up menu of Windows [31].

All the used images, measuring regions, results and other settings are recorded in the file lastwork.h5. This file is located in a subdirectory of the LMK2000 installation folder.

The operation manual LMK 2000 suggested by the software company Techno Team is very crowded and detailed. During the work with the manual the author found a good solution and proposes an algorithm for luminance and illuminance calculation below [32].

4.3 New proposed algorithm for luminance calculation

Step 1. Commands for *Capturing images*

Find the commands for capturing images in the pop-up menu Capture or by clicking on the corresponding icon in the tool bar.

"Luminance" images can be captured using the menu items Capture | SinglePic, Capture | MultiPic and Capture | HighDyn, as well as via the corresponding buttons of the button bar.

Selecting the command Capture | HighDyn several shots are taken but with permanently adapted integration time and then transformed into one single luminance image after calculation.

Capture image

Step 2. To choose *Polygon*

When the desired type has been chosen, the cursor changes its appearance. For each type of a region, a specific cursor is displayed. The region can be of the type of a rectangle, a line, a circle, or a polygon. A polygon is started like a line: press the left-hand mouse button, move the mouse, release the mouse button. After this, all other lines can be added in the same way.

When the polygon has been completed, you can finish the process by:
- a mouse click (pressing and releasing the left-hand mouse button without moving the mouse) or by
- pressing the right-hand mouse button and selecting the standard cursor from the context menu.

Choose polygon

Step 3. To make an evaluation
Image processing
→ new image
→ →Black/White
→ → Name of image (ROAD)
→ → → OK

Step 4. *Equalization*
Image processing
→ Projective equalization Instruction

→ →Select image and regions
→ → Destination Source
→ → → Road Luminance image
→ → → OK

Step 5. To choose *Image size*.

Using the command Image properties the dialogue Image properties will be opened. The current image size is displayed, permitting you to change it whenever you want. The data concerning the first column or line indicate the position of the top left hand corner, the data concerning the columns and lines indicate the height and the width, respectively, of the image.

The size of evaluation images can freely be chosen. The data concerning the size of the camera image or also the luminance image can be modified. However, when capturing a camera image or a luminance image, the size will be reset to the default values preset by the hardware.

If a rectangle is marked within the image, there is the button On marked region available. When you press this button, the image size is reduced to the size of that rectangle.

You should delete this rectangle after leaving the dialogue because its size is the same as that of the image itself and it is still marked. (Press the right mouse button and select the menu item Delete.)

Image properties

Change new Image properties

For example:
Lines → 1000
Columns → 600
1st line →0
1st column → 0

Step 6. To choose a new rectangle

With the exception of the polygon, new measuring regions can also be entered via a dialogue**.** The dialogue Create new region can be opened via the menu item Regions | New Region | Via Dialogue. After choosing a type of a region, the parameters for the new region can be set. When you press the button Add region, the new region will appear in the image.

Rectangle

Modified new rectangle

For example:

Left	→	0
Top	→	0
With	→	600
Height	→	1000

Add region→OK

Step 7. To choose the *Coordinate system*

With the properties of the coordinate system an existing coordinate system can be chosen. All properties will be shown in the dialogue, some of them can be edited. The common properties, which are available for all types of coordinate systems are shown on the left-hand side of the dialogue. On the right-hand side of the dialogue, the properties relating to a definite type of coordinate system are shown or can be edited.

Choose system

Selecting the button *New*, a new coordinate system can be defined. The dialogue New coordinate system is opened where the name and the type of the new coordinate system must be assigned. Five different types are available at this moment:

Scaling and shifting factors and offsets to horizontal and vertical extensions can be assigned by using this type.

When using type Default of the coordinate system no numeric properties can be set. Only the name of the axis can be assigned.

The predefined coordinate system for a displaying camera, luminance and evaluation images are a Default type and named Default. The properties of this predefined coordinate system cannot be changed. However, it is possible to define one's own Default-type coordinate system. Here, one's own assignments, e.g. for the x- and y-axis or for the units can be determined.

Image
Coordinate system
Assign
Save
Close dialogue

A coordinate system can be assigned to each of the images. The purpose of such systems is the change of the pixel-wise display of local coordinates to a representation, which is better adapted to the problems to be solved.

After the definition of a coordinate system all representations of position, height, width, length and areas are given in the assigned values and units.

By using the new coordinate system, only the extensions of an image will be shown in another form than before. In contrast to that, a new image must be calculated in the case of a coordinate transformation.

Step 8. To choose a measurement point

Regions
→Properties
→ →Properties of regions
→ → New region
→ → → →Type of region
→ → → → Circle
→ → → → →Properties of region
→ → → → → Central point (X) →50
→ → → → → →Central point (Y) →50
→ → → → → → Radius →10

Step 9. Dublicate measurement point

Dublicate

Horizontal number →5
Horizontal distance →100
Vertical number→10
Vertical distance →100
→OK

4.4 New proposed algorithm for illuminance calculation

Step 1. Commands for *Capturing images*

You can find the commands for capturing images in the pop-up menu Capture or by clicking on the corresponding icon in the tool bar.

"Luminance" images can be captured using the menu items Capture | SinglePic, Capture | MultiPic and Capture | HighDyn, as well as via the corresponding buttons of the button bar.Selecting the command Capture | HighDyn several shots are taken but with permanently adapted integration time and then transformed into one single luminance image after calculation.

Capture image

Step 2. To choose *Polygon*

When the desired type has been chosen, the cursor changes its appearance. For each type of a region, a specific cursor is displayed. The region can be of the type of a rectangle, a line, a circle, or a polygon. A polygon is started like a line: Press the left-hand mouse button, move the mouse, release the mouse button. After this, all other lines can be added in the same way.

When the polygon has been completed, you can finish the process by:
- a mouse click (pressing and releasing the left-hand mouse button without moving the mouse) or by
- pressing the right-hand mouse button and selecting the standard cursor from the context menu.

Choose polygon

Step 3. To make an evaluation
Image processing
→new image
→ Black/White
→ →Name of image (ROAD, FOOT-PATH)
→ → →OK

Step 4. Equalization

Image processing
→ Projective equalization →Instruction

→	→	Select image and regions			
→	→	Destination	→	→	Source
→	→	Pedestrian	→	Luminance image	
→	→	→OK			

Step 5. To choose *Image size*.

Using the command Image properties the dialogue Image properties will be opened. The current image size is displayed, permitting you to change it whenever you want. The data concerning the first column or line indicate the position of the top left-hand corner, the data concerning the columns and lines indicate the height and the width, respectively, of the image.

The size of evaluation images can freely be chosen. The data concerning the size of the camera image or also the luminance image can be modified. However, when capturing a camera image or a luminance image, the size will be reset to the default values preset by the hardware.

If a rectangle is marked within the image, there is the button On marked region available. When you press this button, the image size is reduced to the size of that rectangle.You should delete this rectangle after leaving the dialogue because its size is the same as that of the image itself and it is still marked. (Press the right mouse button and select the menu item Delete.)

Image properties

Change new Image properties

Lines	→1000
Columns	→500
1st line	→0
1st column	→0

Step 6. To choose a new rectangle

With the exception of the polygon, new measuring regions can also be entered via a dialogue. The dialogue Create new region can be opened via the menu item Regions | New Region | Via Dialogue. After choosing a type of a region, the parameters for the new region can be set. When you press the button Add the region, the new region will appear in the image.

Rectangle

Modified new rectangle

Left →0
Top →0
Width →500
Height →1000

Add region→OK

Step 7. To choose the coordinate system

With the properties of the coordinate system an existing coordinate system can be chosen. All properties will be shown in the dialogue, some of them can be edited. The common properties, which are available for all types of coordinate systems are shown on left-hand side of the dialogue. On the right hand side of the dialogue, the properties relating to a definite type of coordinate systems are shown or can be edited.

Choose system

Selecting the button New, a new coordinate system can be defined. The dialogue New coordinate system is opened where the name and the type of the new coordinate system must be assigned. Five different types are available at this moment:

Scaling and shifting factors and offsets to horizontal and vertical extensions can be assigned by using this type.When using the type Default of the coordinate system no numeric properties can be set. Only the name of the axis can be assigned.

The predefined coordinate system for a displaying camera, luminance and evaluation images are a Default type and named Default. The properties of this predefined coordinate system cannot be changed. However, it is possible to define one's own Default-type coordinate system. Here, one's own assignments, e.g. for the x- and y-axis or for the units can be determined.

Image
→ Coordinate system
→ →Assign
→ → Save
→ → → Close dialogue

Step 8. Illumination (see step 3 to make a new evaluation)

Image processing
→ new image
→ → Black/White
→ → → Name of image (ILLUMINATION)
→ → → OK

Step 9. To choose the physical quantity and unit

Image processing
→ Physical quantity and unit
→ → Select image Illumination
→ → OK
Value E
Unit lx

Change unit
L → E

Step 10. Image processing
→ Image arithmetic
→ → Select operation and operands
MULTIPLICATION

Multiplication

Destination operand → Source operand1 → Source operand2
Illumination → Pedestrian → Constant
→ → → → → OK

Constant 10.83 → → → OK

The general conversion formula:

$$L = \frac{\rho \times E}{\pi} \tag{13}$$

$$E = \frac{\pi \times L}{\rho} \tag{14}$$

→ E=Efotometer (to be measured separately)

Reflection coef. For example, 0.29, $E\kappa = \frac{3.14}{0.29} = 10.83$

Step 11. Repeat Step 6 (To choose a new rectangle)

With the exception of the polygon, new measuring regions can also be entered via a dialogue. The dialogue Create new region can be opened via the menu item Regions | New Region | Via Dialogue. After choosing a type of a region, the parameters for the new region can be set. When you press the button Add region, the new region will appear in the image.

Left →0
Top →0
Width →500
Height →1000

Add region→OK

Step 12. To choose a measurement point
Regions
→ Properties
→ → Properties of regions
→ → → New region
→ → → → Type of region
→ → → → → Circle
→ → → → → → Properties of region
→ → → → → → Central point (X) 50
→ → → → → → Central point (Y) 50
→ → → → → → Radius 10
Step 13 DUBLICATE the measurement point

Dublicate

Horizontal number →5
Horizontal distance →100
Vertical number→10
Vertical distance →100
OK

The algorithm for the calculation of luminance and illuminance is presented in Appendix D.

5. EXPERIMENTAL VERIFICATION OF THE DEVELOPED ALGORITHM

5.1 Luminance measurement with digital cameras

The camera is an advanced digital CCD camera system including a very precise analogue electronic system for signal generation.

Fig. 22. LMK mobile advanced Canon 350D

In this camera Fig. 22 sensors made by Sony company, type CMOS Canon ASP-C and lens Sigma 18-50 mm F2.8 EX DC (calibrated for luminance measurements) are used. Luminance resolution is 1728(H) x 1152(V). Measuring range can be selected manually M (Manual capture mode) or using the aperture priority function A_v (Aperture priority mode) by selecting aperture value, exposure time and ISO speed. Using the A_v function, the camera automatically selects an exposure time, which is suitable for the brightness of the object to be captured.

Light sensitivity (accuracy rating) is shown in Table 10.

Table 10. Light sensitivity

Aperture	4	4	4
ISO	100	1600	100
t_i=0.001 s	15 kcd/m^2	900 cd/m^2	100 cd/m^2
t_i=3.0 s	5 cd/m^2	0.3 cd/m^2	40 cd/m^2

It should be taken into account that the luminance measurement camera is not spectral matched to the $V(\lambda)$ visibility curve of the human eye. This is due the use of RGB filters instead.
In view of the above details, accuracy is as follows:
- the overall accuracy can be specified as a combination of calibration uncertainty and system uncertainty;
- the smallest overall uncertainty is 5.8% (k=2).

Measuring uncertainty ΔL in % (for standard illuminant A) is shown in Table 11.

Table 11 Measuring uncertainty ΔL in %

T_i/A_v	4	5.6	8	11
0.25 ms	7.6	8.0	8.2	8.8
2.5 ms	6.0	6.3	6.5	7.2
25 ms	5.8	6.2	6.4	7.0
0.25 s	5.8	6.2	6.4	7.0
2.5 s	5.8	6.2	6.4	7.0

Memory per image is approximately 9 MB, operating system Windows 2000/XP, Software-LMK 2000.

The author is the first in Estonia to attempt to do some measurements by the camera Canon 350D. The camera is calibrated for luminance measurements with adjusted apertures between $F_4 \leq F_x \leq F_{11}$. For these aperture values a compensation for the vignetting effect inside the lenses was carried out (shading compensation). The camera can be used with all focal lengths (18 – 50) mm offered by the Sigma lens.

To take a measurement, the mode dial will have to be set either to manual capture mode ‘M’ or to Aperture priority mode ‘A_v’. In these two modes, the aperture can be set manually to a value between F_4 and F_{11}. Using the aperture priority function, the camera automatically selects an exposure time, which is suitable for the brightness of the object to be captured.

If luminance images will be captured, the function compression method ‘RAW’ or ‘RAW+L’ (capture of uncompressed images) must explicitly be adjusted on the camera. Compressed images (JPG images) cannot be evaluated for luminance measurements.

The function ‘HighDyn’ of the LMK software enlarges the dynamic range by utilizing the Auto Exposure Bracketing (AEB) function of the camera.
An exposure series of three captures are processed to form one image. The maximum dynamic range comprises ±2 Exposure Values (EV). The starting exposure times of the exposure series should suitably be chosen between 1/1250 sec. $\leq T_i \leq$ 8 sec.

This AEB setting must be made each time the camera is started.
Luminance captures should always be taken with the AEB function being activated. Then, the image series captured will be processed to HighDyn luminance or also colour shots by means of the LMK2000 software. Furthermore, for taking exposure series, a tripod will always be necessary.

The camera offers three methods of exposure measurement – evaluative metering, partial metering and center weighted integral measurement. When the shutter button of the camera is pressed halfway, the measuring method chosen will be shown on the LCD display.

For practical applications, it can be useful to differentiate between the following situations:

- homogeneous scenes
- scenes with small light sources of high luminance
- dark scenes

Homogeneous scenes - these include scenes presenting a largely homogeneous level of brightness. For this kind of luminance measurements, the evaluative metering is recommendable. Here, attention must be paid to the fact that the autofocus of the camera is activated.

Scenes with small light sources of high luminance - in the case of such scenes, the evaluative metering performed by the camera often determines too long exposure times. This can result in the fact that – even in the case of HighDyn captures - the LMK2000 evaluation software cannot evaluate the interesting image regions presenting those high luminances. In such a situation, it is recommendable to utilize the partial metering or also the center-weighted integral measurement function of the camera. Here, however, attention has to be paid to the fact that the object to be evaluated is aligned to the center of the image. If the object cannot be aligned or if the exposure measurement yields wrong values nevertheless, measurement must be adapted by setting the exposure compensation function.

Dark scenes - if the dark regions of a mixed scene are of interest, the evaluative metering could possibly yield too short exposure times, which would result in insufficient loads of the dark regions. Also in this case, it is necessary to apply the partial metering or the center-weighted integral measurement, depending on the size of the object concerned. If this is not possible or if the exposure measurement yields wrong values nevertheless, it must again be adapted by setting the exposure compensation function.
Features of the Canon 350D:

- complex evaluation of luminous and illuminated scenes by means of the photograph of an image-resolved luminance distribution;
- simultaneous recording of a volume of connected measuring data;
- easy data analysis (at a glance);
- luminance distributions in measuring images L(x,y);
- derived lighting-engineering parameters, such as illuminance distribution *E(x,y)* and luminous intensity distribution *I(x,y)*
- statistical data to be used in calculation programs (z.B. EXCEL, MatLAB, LabVIEW).

Applicaton of the Canon 350D:

- night design
- measurement of headlamps
- measurement of lamps and luminaires
- exterior lighting roads and tunnels
- interior lighting
- display measuring

5.2. Illuminance light calculation and measurement for the Siili Park

A specific standard method was used: professional light planning, calculation and visualization by software Dialux.

Dialux software is intended for light planning, calculation and visualization of outdoor (and indoor) lighting systems. Dialux software is free and was available to be imported from and exported to CAD programmers and included photorealistic visualization with an integrated ray tracer.
Most of the major manufacturers provide also free luminaires data for users.

The S class is intended for pedestrians and pedal cyclists for use on footways and cycle ways, emergency lanes and other road areas lying separately or along the carriageway of a traffic route, residential roads, pedestrian streets, parking areas, schoolyards, etc.

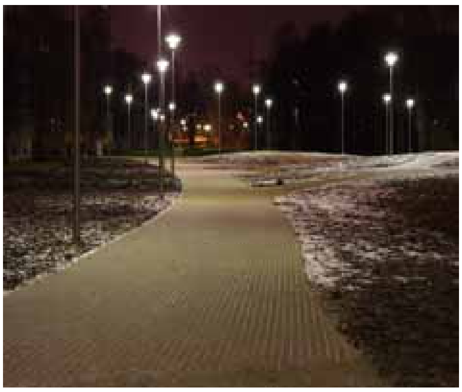


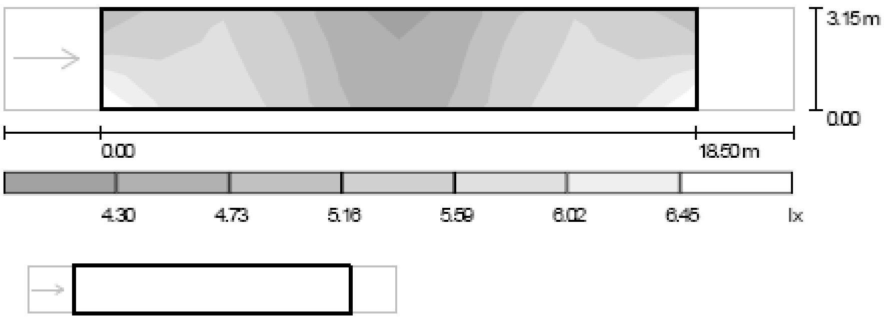
Fig. 23. Siili Park

For illuminance light calculations for the Siili park Fig. 23 it is essential to acquire some parameters, such as road class, road surface, pole height, luminaire power, which are presented in Table 12.

Table 12. Parameters for light calculation in the Siili Park

Road⁄Street	Park
Road class	S2
Road surface class	C2
Road width	3,15
Row	1
Pole height m	6
Console light m	0
Luminaire power W	70
Poles interdistance	18.5

The DIALux software enabled the author to compose a model for illuminance requirements according the standard, which is shown in Fig. 24 and in Appendix E.



2.625	5.12	5.56	5.67	4.75	4.23	4.23	4.75	5.67	5.57	5.12
1.575	5.58	5.50	5.90	4.96	4.39	4.39	4.96	5.90	5.50	5.59
0.525	6.36	5.40	5.99	5.04	4.46	4.46	5.04	5.99	5.41	6.36
m	0.925	2.775	4.625	6.475	8.325	10.175	12.025	13.875	15.725	17.575

Fig. 24 Calculation by the DIALux software for the Siili Park illumination

According to the calculation the following parameters were obtained:

E_{aver}=5.26 lx

E_{min}=4.2 lx

E_{max}=6.36lx

E_{min}/E_{aver}=0.80

E_{min}/E_{max}=0.66

For light measurements it is essential to acquire the parameters presented in Table 13.

Table 13. Parameters for the study of the Siili Park

Road/Street	Siili Park
Date	2007-11-11
Time	23.00-00.00
Road surface	stone
Pole height m	6
Console light m	0
Luminaire power W	70
Weather	dry
Temperature C°	-5 C°
Visibility	good
Road condition	dry

The protocol in Fig. 25 shows a measurement made from a real scenario in the luminance picture.

According to the algorithm used the functionality of the "projective rectification" with the market polygon region in the luminance picture as the source region and a market region in "pseudocolor" as the target, this result can be rebuilt.

To calculate the lengthwise uniformity, the standard Excel-table is copied with the result of the picture into the insert position in the Excel-File "*Excel_Road_Evaluation*".

For copying the table, make a right click on the table and go to "copy", after that in MS-Excel click go to "Edit"   "Insert" (Ctrl+V).

The calculation and the protocol are presented in Appendix E.

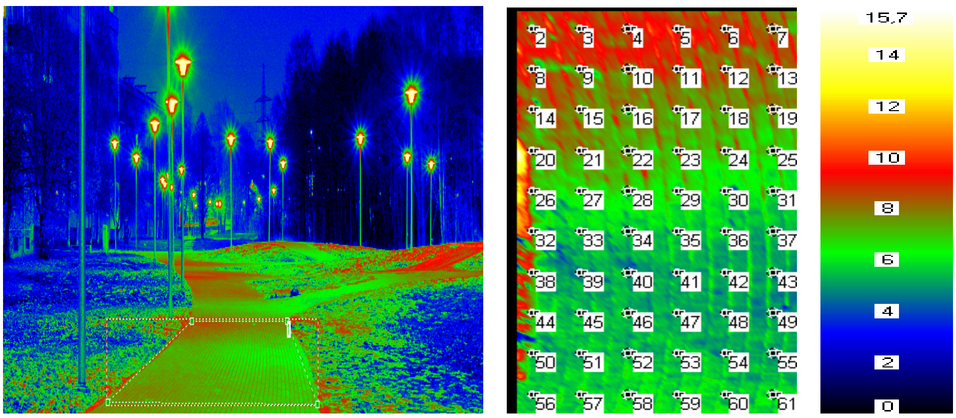


Fig. 25. Protocol of measurement of the Siili Park illumination

Study results and a comparison of the results are presented in Table 14.

Table 14 Comparison of illumination

		Standard EVS-EN 13201		Calculation		LMK 2000 software	
Park	Class	E_{mid} lx	E_{min} lx	E_{mid} lx	E_{min} lx	E_{mid} lx	Em_{in} lx
Siili Park	S2	10	3	3.87	3.57	6.75	4.7

Based on the measurement and comparison with the standard numbers, it was revealed that park illumination is not suitable.
The calculation and the protocol of measurement of the Siili Park are presented in Appendix E.

5.3. Luminance light calculation for Männiku tee, Kadaka tee, Tähesaju tee, and Tondi street

The specific standard method was used: professional light planning, calculation and visualization software (Used: Dialux, Relux).

This software is intended for light planning, calculation and visualization of outdoor (and indoor) lighting systems. Some softwares are free and others have the ability to import from and export to CAD programmes and include photorealistic visualization with an integrated ray tracer.

Most of the major manufacturers provide also free luminaire data for users. Most of that software aims to take the latest standards into consideration as well as planning regulations and customs of the specific country.

To calculate the average roadway luminance and uniformity of luminance, it is necessary to know the luminous intensity distribution of the luminaries, the luminous flux of the lamps, the geometry of the installation and the reflective properties of the road surfaces.

For light calculation it is essential to acquire the parameters presented in Table 15.

Table 15 Parameters for light calculation

Road/Street	Männiku tee	Kadaka tee	Tähesaju tee	Tondi street
Road class	ME2	ME3	ME3	ME4
Road surface class	C2	C2	C2	C2
Road width	16.5	10.5	7.5	7.0
Row	2+2	2+1	1+1	1+1
Pole height m	12	9	12	10
Console light m	2.5	2.5	2.5	1.0
Luminaire power W (HPS sodium lamp)	250	250	250	250
Poles interdistance	27	28	32.6	28.4

Results of the calculation are explained in the next pictures in Fig. 26 Fig. 27 Fig. 28 Fig. 29 and in Appendix E.

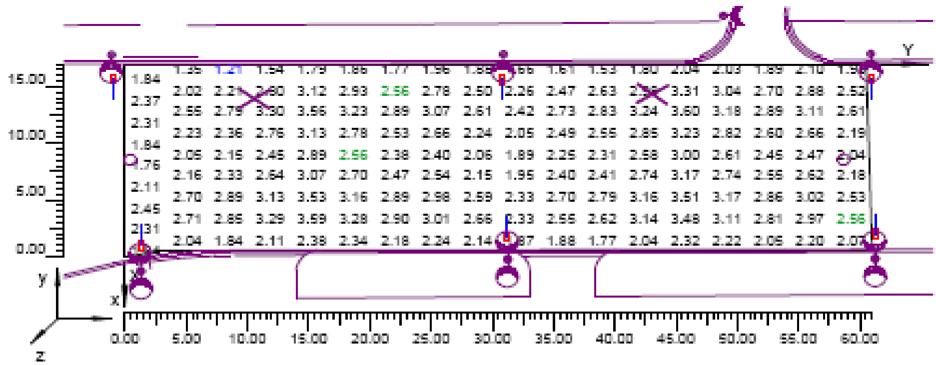
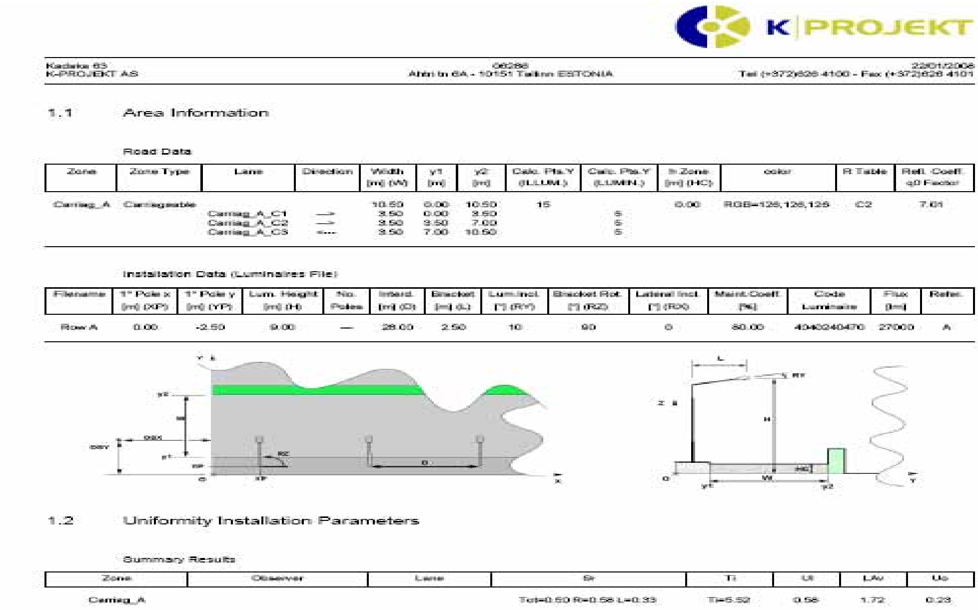


Fig. 26. Calculation of Männiku tee illumination by RELUX software



Kadaka 63
K-PROJEKT AS

06286
Ahtri tn 6A - 10151 Tallinn ESTONIA

22/01/2006
Tel (+372)626 4100 - Fax (+372)626 4101

1.1 Area Information

Road Data

Zone	Zone Type	Lane	Direction	Width [m] (W)	y1 [m]	y2 [m]	Calc. Pts.Y (ILLUM.)	Calc. Pts.Y (LUMIN.)	h Zone [m] (HC)	color	R Table	Refl. Coeff. q0 Factor
Carriag_A	Carriageable			10.50	0.00	10.50	15		0.00	RGB=126,126,126	C2	7.01
		Carriag_A_C1	--->	3.50	0.00	3.50		5				
		Carriag_A_C2	--->	3.50	3.50	7.00		5				
		Carriag_A_C3	<---	3.50	7.00	10.50		5				

Installation Data (Luminaires File)

Filename	1° Pole x [m] (XP)	1° Pole y [m] (YP)	Lum. Height [m] (H)	No. Poles	Interd. [m] (D)	Bracket [m] (L)	Lum.Incl. [°] (RY)	Bracket Rot. [°] (RZ)	Lateral Incl. [°] (RX)	Maint.Coeff. [%]	Code Luminaire	Flux [lm]	Refer.
Row A	0.00	-2.50	9.00	---	28.00	2.50	10	90	0	80.00	4040240470	27000	A

1.2 Uniformity Installation Parameters

Summary Results

Zone	Observer	Lane	Sr	TI	Ul	LAv	Uo
Carriag_A			Tot=0.50 R=0.58 L=0.33	TI=5.52	0.58	1.72	0.23

Fig. 27. Calculation of Kadaka tee illumination by RELUX software

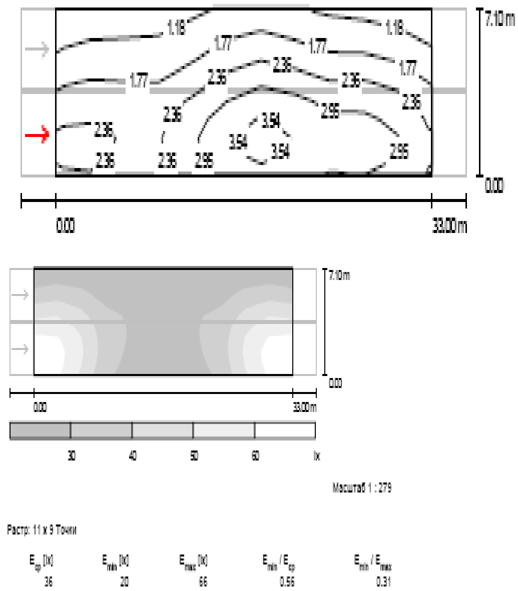


Fig. 28. Calculation of Tähesaju tee illumination by DIALux software

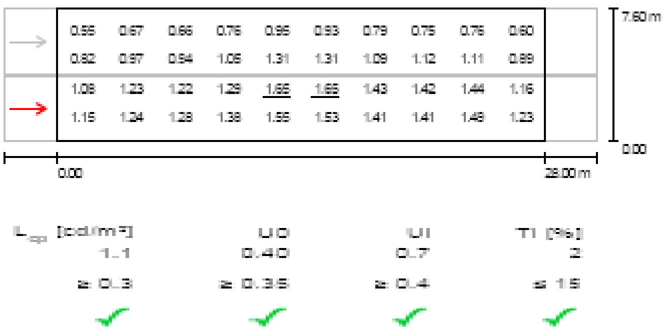


Fig. 29. Calculation of Tondi street illumination by DIALux software

Also, some examples of a project for Kadaka tee and Männiku tee are presented in Fig. 30, 31 and Appendix E.

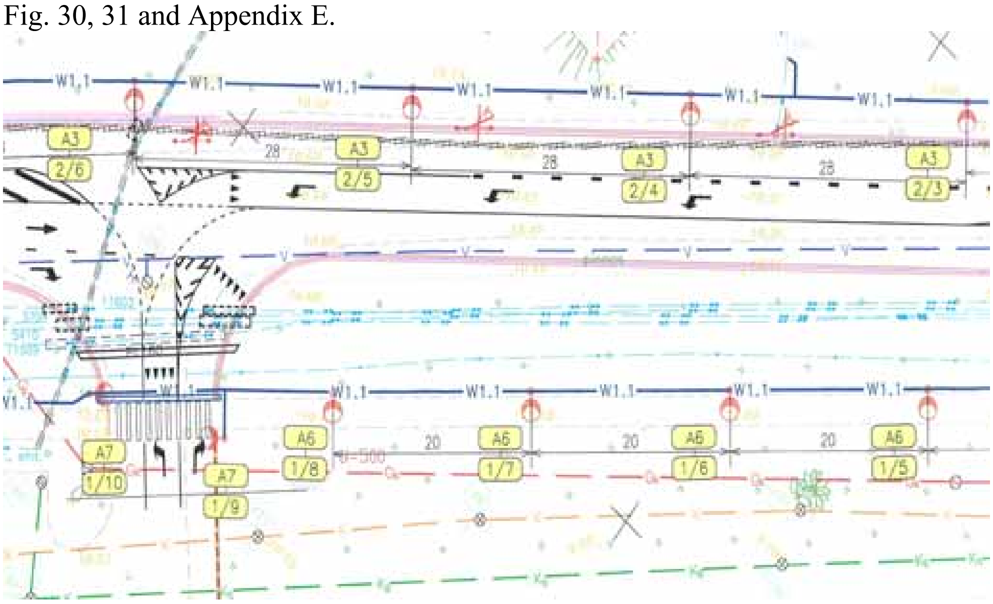


Fig. 30. Kadaka tee project by firm K-Projekt

Fig. 31. Männiku tee project by firm K-Projekt

5.5 Luminance measurement for Männiku tee, Kadaka tee, Tähesaju tee and Tondi street

The spatially resolved analysis of light sources and illuminated scenes is becoming increasingly important. The complex evaluation of those scenes requires knowledge of the luminance distribution within the whole field of view or at least in many selected parts of it. Solving the necessary measuring tasks by means of measuring devices working point by point either takes an enormous amount of time or is possible only within a coarse raster grid or is not possible at all. Thus, the development of spatially resolved radiation receivers, in particular CCD matrix cameras, has enabled the user to solve measuring problems, such as measurements of visibility conditions in the road traffic at night.

For light measurements it is important to know the parameters presented in Table 16.

Table 16. Road and street research condition

Road⁄Street	Männiku tee	Kadaka tee	Tähesaju tee	Tondi street
Date	2008-02-19	2007-10-25	2007-10-25	2008-02-19
Time	23.00-00.00	00.00-01.00	00.00-01.00	23.00-00.00
Road surface	Asphalt (C2)	Asphalt (C2)	Asphalt (C2)	Asphalt (C2)
Pole height m	12	9	12	10
Console light m	2.5	2.5	2.5	1.0
Luminaire power W	250	250	250	150
Weather	dry	dry	dry	dry
Temperature C^o	-5 C^o	2 C^o	2 C^o	-5 C
Visibility	good	good	good	good
Road condition	dry	dry	dry	dry

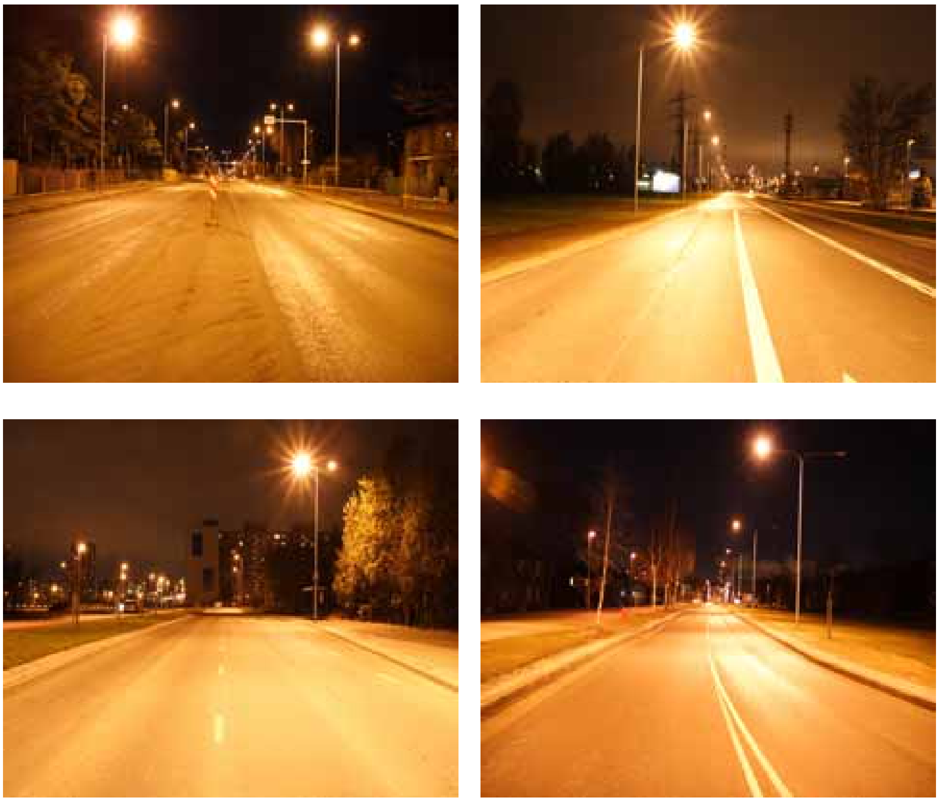


Fig. 32. Camera Canon 350D images of Männiku tee, Kadaka tee, Tähesaju tee and Tondi street

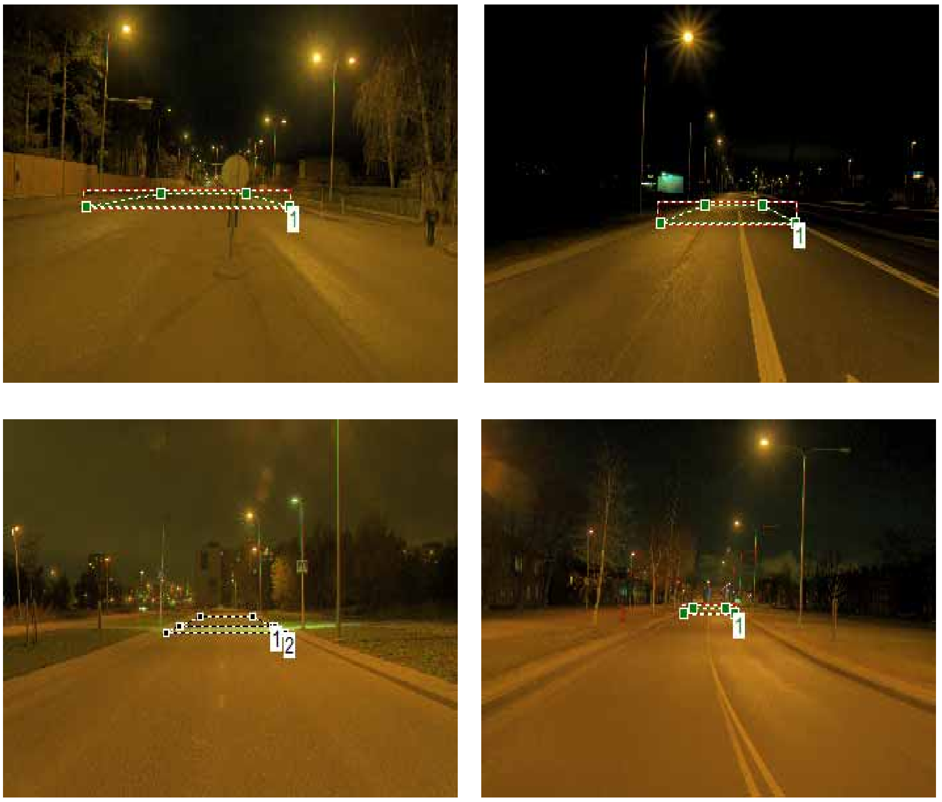


Fig. 33. Camera Canon image 350D with the polygon of Männiku tee, Kadaka tee, Tähesaju tee

The LMK2000 Operation Manual is an aid to get quick measurement results of illuminated street scenes according to the standard EVS EN 13201- 3:2003. The standard determines all the criteria (average luminance, overall uniformity and longitudinal uniformity) and describes all the measurement conditions for the lighting of streets.

The standard EN 13201-3:2003 is assumed to a street with two driving direction lanes and specifies a measurement area over one lane, between two street luminaires.

The leading edge of this area is 60 meters in front of the position of the observer.
The height of the observing position is given with 1.5 meters and the optical alignment is parallel to the street surface and in the middle of a driving direction lane.

According to LMK2000 – Software rules can align a measurement region (polygon) in luminance or evaluation image (Fig. 34).

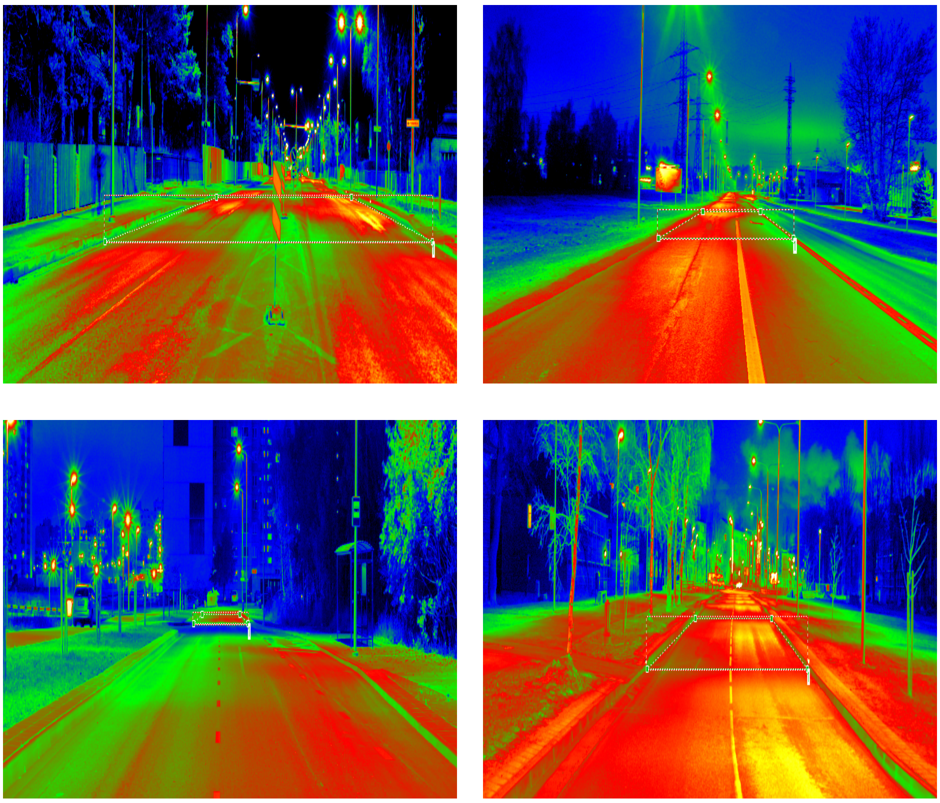


Fig. 34. Software pseudocolour presentation of Männiku tee, Kadaka tee, Tähesaju tee and Tondi street

According to the recommendation for a perspective to be absolutely fitting, distorted image should place some marks (e.g. signs with 60m, 100m and so on) in the real measurement scene.

To get a first overview about the measurement results, a pseudo colouring mode of the image is implemented. In the basic settings of this colouring mode, there is a linear scaled range of colours, every colour means one luminance value.

After placing a measurement region according to the standard, you can see the measurement results for the average luminance in the inspector tab window in the register standard in the tab table.
As a result, the table of the measurement results is represented as follows:

Average luminance:	L_{mean} = “Mean“ in [cd/m²]
Minimal Luminance:	L_{min} = “Min“ in [cd/m²]
Maximal Luminance:	L_{max} = “Max“ in [cd/m²]
Overall uniformity (result of line equation):	$U_o = L_{min} / L_{mean}$

The standard EN 13201-3:2003 is using a method based on a spot matrix to verify the longitudinal uniformity. According to this norm, the image evaluation protocol LMK2000_Road_expl.h5 includes such measurement spots, as regions for the projective equalization.

There is an Excel-Sheet attached to the manual that calculates the longitudinal uniformity of the luminance automatically.

Using the algorithm (Appendix D) – to calculate street luminance according to EN 13201-3:2003 interactive on a PC the Excel-Sheet can be used by double click on the icon.

The Excel-Sheet calculates the longitudinal uniformity and shows the results in the yellow market fields (Appendix E).

The results of comparison are presented in Table 17. Also, protocols are given in Appendix E.

Table 17. Comparison results

Road⁄Street	Road class	Standard EVS-EN 13201			Calculation			LMK measurment		
		L cd/m^2	U_o	U_l	L cd/m^2	U_o	U_l	L cd/m^2	U_o	U_l
Männiku tee	ME2	1.5	0.4	0.7	3.2*	0.47	0.68	1.91	0.54	0.38
Kadaka tee	ME3	1	0.4	0.6	1.72	0.23	0.58	4.03	0.47	0.29
Tähesaju tee	ME3	1	0.4	0.6	2.2	0.38	0.40	2.22	0.55	0.77
Tondi street	ME4	0.75	0.4	0.5	1.1	0.40	0.70	0.56	0.49	0.50

Today designers use the minimum values recommended in EN 13201 according to which streets and roads are constructed by road engineers. The measurement results are shown in the figure (Fig. 35 and Table 18).

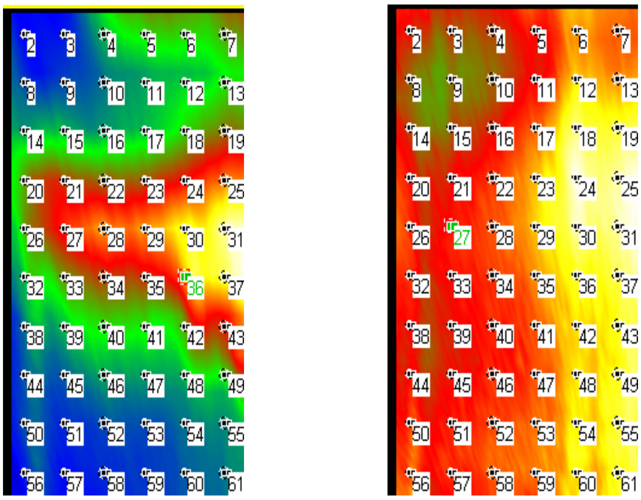


Fig. 35. Polygon of Tondi tee and Tähesaju tee

Table 18. Minimum luminance by points of polygon

Point	2	8	14	20	26	32	38	44	50	56
Tondi tee L cd/m²	0.429	0.541	0.679	0.980	0.945	0.735	0.606	0.558	0.542	0.463
Tähesaju tee	1.508	1.361	1.428	1.578	1.64	1.639	1.561	1.557	1.661	1.695

The author's recommendation to the designers is to calculate average luminance of the road surface in the range 0.8 cd/m² to 2.5 cd/m². It will decrease road accidents and provide a good vision.

6. CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

This doctoral work has developed a theoretical and practical application-oriented knowledge base aiming at improved road and street safety during darkness. Some street parts were analyzed and tested and parameters are recommended to satisfy lighting criteria requirements needed to enable drivers to make out shapes of the presence of people and objects in the traffic area.

The lighting planner is recommended to meet the requirements set in road safety standards and regulations for luminance, longitudinal and overall uniformity and glare limitation. The result should be a clear "image" of the road ahead. The main results of the research and analyses are as follows:

1. classification and analysis of the recent state of the art issues and current trends of similar systems and methods;
2. development of a standard as a result of the analysis of the existing performance requirements and limitations for road calculation (analyses of standards and norms) to determine the optimal design requirements. The standard is recommended for the average luminance of the road surface to be in the range 0.3 cd/m^2 to 2 cd/m^2. It is estimated that an increase in luminance of 0.5 cd/m^2 leads to a 35% will lead to a decrease in road accidents.
3. development of an original algorithm for illuminance and luminance calculation, which can save time and resources;
4. comparison of the calculated values and standard values by the use of different programme software and comparison of both of them with measurement values;
5. comparison of the luminance and illuminance photometers and the luminance measurement camera showed that the former which works point by point takes an enormous amount of time, whereas with the latter with the CCD matrix only a few minutes are required for measurement.

Advantages of the luminance measurement by camera:

- complex evaluation of luminous and illuminated scenes by means of the photograph of an image-resolved luminance distribution;
- simultaneous recording of a large volume of connected measuring data, easy data analysis.

6.2 Future work

As mentioned above, the luminance measurement camera has some advantages over other types. Certainly for future research it is essential to save time and resources.

First, the author will propose the recommendations developed to Tallinn City Council to be used for taking measurements in many problem places on the roads and streets.

Second, the author is planning to draw a map of road and street lighting measurement of Tallinn.

Third, research is to be continued for streets and roads (newly built) related to the field of measurement and also as a regular service to be proposed.

Fourth, the author intends to develop an algorithm for indoor and outdoor glare calculation.

Fifth, research for glare evaluation according to the UGR (Unified Glare Ratio) method and calculation to be conducted.

Thus, the development of spatially resolved radiation receivers, in particular CCD matrix cameras, has enabled the user to solve measuring problems, such as measurements for glare evaluation according to the UGR method, the analysis of visibility conditions in the road traffic at night, emissions evaluations of glare sources, and the determination of contrasts in illumination situations (workplace) or directly on light sources (e.g. lamps/luminaires, displays, night design, indicators).

REFERENCES

1. Standard CEN/TR 13201-1:2004 TEEVALGUSTUS Osa 1: Valgustusklasside valik, Eesti standardikeskus. p.28.
2. Standard EVS-EN 13201-2:2007 TEEVALGUSTUS Osa 2: Teostusnõuded, Eesti standardikeskus. p.24.
3. Standard EVS-EN 13201-2:2007 TEEVALGUSTUS Osa 3: Valgussuuruste arvutamine, Eesti standardikeskus. p.41.
4. Standard EVS-EN 13201-2:2007 TEEVALGUSTUS Osa 4: Valgustuse mõõtemeetodid, Eesti standardikeskus. p.16.
5. Standard EVS-EN 843:2003 Linnatänavad, Eesti standardikeskus, p.257.
6. Tallinna Linnavalitsuse 24.03.2004 määrusega nr. 26 kehtestatud ”Tallinna linna teevalgustusnormid”, Tallinn, 2004. p.42.
7. Tallinna Linnavalitsuse 04.05.2005 määrusega nr. 50 kehtestatud ”Jalakäijate reguleerimata ülekäiguradade valgustuse tüüpmoodulid”, 2005.
8. Standard EVS-EN Valgus ja valgustus TÖÖKOHAVALGUSTUS Osa 1: Sisetöökohad, Eesti standardikeskus, p 57.
9. Kavand Töökohtade tehisvalgustuse mõõtmine ja hindamine, Eesti standardikeskus.
10. BURLACU, Camelia., BIANCHI, Cornel., 2001 Conception/design of lighting systems for urban traffic roads, Technical University of Constructions, Bucharest. p. 60.
11. Good Lighting for Safety on Roads, Paths and Squares, 2000. Fördergemeinschaft Gutes Licht, Frankfurt am Main, Germany. p.38.
12. Urban image lighting. 2004. Fördergemeinschaft Gutes Licht, Frankfurt am Main, Germany. p 18.
13. Lighting with Artificalt Light. 2005. Fördergemeinschaft Gutes Licht, Frankfurt am Main, Germany. p 18.
14. Kaufman, J.E., Christensen J.F. 1984. IES Lighting Handbook, Illuminating engineering society of North America, New York.
15. Kaufman, J.E., Christensen J.F. 1987. IES Lighting Handbook, Illuminating engineering society of North America, New York.
16. Commission Internationale de L’Eclairage. 1978. Light as a true visual quantity; Principles of measurement. Publication CIE nr. 42 Central Bureau of CIE.
17. DIN 5044 Stationary traffic lighting – Street lighting for automobile traffic Part 1: General requirements and recommendations Part:2 Calculation and measurement.
18. CIE. 1995. *Recommendation for the Lighting of Roads for Motor and Pedestrian Traffic,* Publication no. 115.
19. Commission Internationale de l’E´ clairage, CIE/IEC. 1987. International Lighting Vocabulary,item 845-03-19. CIE 1987; 17: 4.

20. Commission Internationale de l'E´ clairage. 1989. Mesopic photometry: history, special problemsand practical solutions. CIE Central Bureau CIE 81, 1989.
21. Commission Internationale de l'Éclairage. 1989. *Mesopic Photometry: History, special problems and practical solutions.* Publication CIE No 81. CIE Central Bureau.
22. Commission Internationale de l'Éclairage. 1990. *CIE 1988 2° Spectral luminous efficiency function for photopic vision.* Publication CIE No 86. Vienna. CIE Central Bureau.
23. Commission Internationale de l'Éclairage. 1992. *Fundamentals of the visual task of night driving.* Publication CIE No 100. CIE Central Bureau.
24. Commission Internationale de l'Éclairage. 1995. *Recommendations for the lighting of roads for motor and pedestrian traffic*. Publication CIE No 115. CIE Central Bureau.
25. Dodds, G., Mcmenemy, K., Zatari, A., 2007. Light Measurement method and apparatus, The Queen's University of Belfast, p.45.
26. CCD Technology Primer, www.dalsa.com
27. Schmidt, Franz., Krüger, Udo. 2001. Applications of the image resolved light and color measurement, TechnoTeam Bildverarbeitung GmbH, Ilmenau, p.19.
28. Kinney, J.A.S. 2002. Comparison of scotopic, mesopic, and photopic spectral sensitivity curves. Journal of the Optical Society of America, 48 (3): pp. 185-190.
29. Application & Product Guide 2004, Gigahertz Optik, p.198.
30. PHILIPS, *Lighting Manual*, 5th Edition, Eindhoven, Holland, 1993. p. 170.
31. Image-resolving luminance measurement using luminance measuring cameras type LMK96/98 (Video analyzers). 2001. Techno Team Bildverarbeitung GmbH, Ilmenau.
32. LMK mobile advanced, Operating instructions for the mobile luminance measuring system, based on the Canon EOS 350D digital reflex camera, Techno Team, Bildverarbeitung GmbH, p 20.
33. LMK 2000 Operation Manual, 1995-2005. Techno Team Bildverarbeitung GmbH, Ilmenau, pp.1-115.
34. Poschmann, Ralf., Krüger, Udo., Porsch, Tobias. 2006. Operation Manual LMK2000, Techno Team Bildverarbeitung GmbH, Ilmenau, p.188.
35. Grieneisen, H. Peter., Timmins, S.P. Aline., Sardinha, André S., Couceiro, I. B. Illuminance measurements of Roadways, XVIII IMEKO WORLD CONGRESS Metrology for Sustainable Development September, 17-22,2006, Rio de Janeiro, Brazil.
36. Wolf, Stefan., Gall, Dietrich. Luminance analysers-what they are and how do they work, 25th Session of the CIE, San Diego, 25 June - 2 July 2003.

37. Bianchi, Cornel., Burlacu, Camelia. 2001. Conception/design of lighting systems for urban traffic roads. Technical University of Constructions, Bucharest.
38. Krüger, U., Schmidt, F. 2005 Applied Image Resolved Light- and Color Measurement Introduction and Application Examples. Techno Team Bildverarbeitung GmbH, Ilmenau.
39. Solid State image. 2004.Terminology, Microelectronics technology division Rochester, New York.
40. Paquette, Eric., Poulin, Pierre., and Drettakis, George. A Light Hierarchy for Fast Rendering of Scenes with Many Lights. EUROGRAPHICS '98 / N. Ferreira and M. Göbel, *Volume 17*, (*1998*), *Number 3.*
41. Shaflik, Carl. Environmental effects of roadway lighting, 1999. University of British Columbia Department of Civil Engineering.
42. European Road Lighting Technologies, US DOT FHWA International Technology Exchange Program Office of International Programs, 2001.
43. The language of light www.minoltainstruments.com
44. Eloholma, M., Viikari, M., Halonen, L., Walkey, H., Goodman, T., Alferdinck, J., Freiding, A., Bodrogi, P., Várady, G. 2005. Mesopic models— from brightness matching to visual performance in night time driving: a review. Lighting Research and Technology, p 175.
45. Inanici, Mehlika N. 2004. Transformation of high dynamic images into virtual lighting laboratories, University of Michigan, T. College of Architecture and Urban Planning Ann Arbor. p. 8.
46. Glenn, G., Robinson, J.J., Mullin, R. Assessment of road-lighting parameters using camera based systems. CCTV and Road Surveillance (Ref. No. 1999/126), IEE Seminar on Volume , Issue , 1999 Page(s):5/1 - 5/6.
47. Road transport lighting for developing countries, 2007 CIE Technical report ISBN 978 3 901 906 61 9. p. 50.
48. Metrological Challenges for Quality Measurements with Vision Sensors. D.Hofmann, G. Linss MEASUREMENT SCIENCE REVIEW, Volume 7, Section 1, No. 2, 2007.
49. Cuvalci, Olkan., Ertas, Burga. Roadway lighting design methodology and evalution, 2000 Source, Journal of Integrated Design & Process Science archive Volume 4 , Issue 1 (January 2000).
50. Altpere, Endel. 1981.Valgustehnika käsiraamat, Tallinn, Valgus, p.327.
51. Hentschel, Hans-Jürgen. 1987. Licht und Beleuchtung, Heidelberg. P.377 .
52. Lewin, Ian., 1999 Lamp Color and Visibility in Outdoor Lighting Design, An Advanced Lighting Technologies Company Scottsdale, Arizona, USA.
53. Assessment of road-lighting parameters using camera based systems Dodds, G.; Glenn, J.J.; Robinson, R.; Mullin, F. CCTV and Road Surveillance (Ref. No. 1999/126), IEE Seminar on Volume , Issue , 1999 Page(s):5/1 - 5/6.

54. CIE Road transport lighting for developing countries, CIE technical report, ISBN 978 3 901 906 61 9.
55. Solid state image sensors terminology, Eastman Kodak Company microelectronics technology division, Rochester, New York, 14650-2010, 1994, p.55.
56. LMK 2000 Operation Manual, Techno Team Bildverarbeitung GmbH, 1995-2003, p.115.
57. Image-resolving luminance measurement using luminance measuring cameras type LMK96/98 (Video analyzers), Techno Team Bildverarbeitung GmbH, 2003.
58. Road lighting simulation in Radiance, Radiance Workshop - Fribourg 2004
59. Adrian, W. 2004. Fundamentals of roadway lighting. *Light & Engineering* 12(2):57-71.
60. Berman, S., Clear, R. 2001. Additivity constraints and visual task considerations in mesopic photometry. *Journal of the Illuminating Engineering Society*. Winter 2001: 90-104.
61. Kinney, J.A.S. 1958. Comparison of scotopic, mesopic, and photopic spectral sensitivity curves. *Journal of the Optical Society of America,* 48(3): 185-190.
62. Lamble D., Summala H., Hyvärinen L. 2002. Driving performance of drivers with impaired central visual field acuity. *Accident Analysis and Preception* 34(5): 711-716.

APPENDICES
APPENDIX A
PUBLICATION

1. СИСТЕМА УПРАВЛЕНИЯ ТОННЕЛЯ Елена Армас, Юхан Лаугис; Automation and control technologies 2004; ISBN 9955-09-644-6, pp. 46-50.
2. Tunnel lighting J.Armas, J.Laugis; 2nd International Symposium "Topical Problems of Education in the Field of Electrical and Power Engineering" Doctoral School of Energy and Geotechnologi, 2005 ISBN 9985-69-033-8, pp. 73-79.
3. Emergency Lighting J. Armas; 3rd International Symposium "Topical Problems of Education in the Field of Electrical and Power Engineering" Doctoral School of Energy and Geotechnologi, 2006 ISBN 9985-69-036-2, pp. 138-144.
4. Emergency Escape Lighting Systems J.Armas; Electrical and Control Technologies 2006; ISBN 9955-25-054-2; UDK.621.3(474.5)(06); 681.5(474.5)(06), pp. 162-165.
5. Emergency Escape Lighting Systems J.Armas; Electrical and Control Technologies 2006; ISSN 1822-5934; UDK.621.3(474.5)(06); 681. 5(474.5)(06), pp. 396-400.
6. Road Safety by improved road lighting: road lighting measurments and analyzing J.Armas, J.Laugis 4th International Symposium "Topical Problems of Education in the Field of Electrical and Power Engineering" Doctoral School of Energy and Geotechnologi, 2007, ISBN 978-9985-69-041-3, pp. 83-90.
7. Hädavalgustuse projekteerimine J.Armas, Elektriala nr.1, 2007, lk. 30-31.
8. Road lighting measurements and analysis J.Armas, J.Laugis Proceedings of the 2nd International Conference on Electrical and control technologies 2007; UDK 621.31 (474.5) (06), 681.5(474.5)(06), pp.30-36.
9. Increase pedestrian safety by critical crossroads: lighting measurements and analysis, J.Armas, J.Laugis 12 th European Conference on Power Electronics and Application EPE 2007 ISBN: 97890758150108/IEEE Catalog Number 07EX1656C
10. Quality in artificial lighting, good lighting for safety on roads J.Armas, J.Laugis 5th International Symposium "Topical Problems of Education in the Field of Electrical and Power Engineering" Doctoral School of Energy and Geotechnologi, 2008, ISBN 978-9985-69-046-8, pp. 32-38

APPENDIX B

CURRICULUM VITAE

1. Personal information

Name: Jelena Armas
Date and place of birth: 15.09.1960, Tallinn
Citizenship: Estonian
Marital status: unmarried
Children: daughter Aleksandra Armas,

2. Contact information

Address: Uus – Sadama 22-5, 10120, Tallinn
Telephone: (+372) 5107670
E-mail: jarmas@hot.ee

3. Educational history

Institution	Graduation date	Education
Tallinn University of Technology	1982	Dipl. Electrical Engineer
Tallinn Secondary School No 6	1979	Basic

4. Languages

Language	Level
Russian	Excellent
English	Good
Estonian	Good

5. Professional employment

Date	Organization	Position
1982 - 1985	Tallinn University of Technology	engineer, researcher
1985 - 1995	AS Printall	electrical engineer
1994 - 1996	AS Balti Ekspeditsioon	manager
1996 - 2001	AS Printall	supervisor
2001 - 2001	AS Keila Veskid	supervisor
2002 - 2006	EA Reng AS	engineer
2006 -.	OÜ Jaotusvõrk	specialist

6. Special courses

Date	Organization
1998	OÜ Ohutusekspert “ Instruction for low power installations of buildings”
1999	International House “ Intermediate course in general English”
2000	E-Katedraal “Training course of fire safety”
2002	AS PE Konsultant “Client communication”
2006	Meta Profit “Managing contacts with problem clients”
2008	Meta Profit “Stress management and communication technology”

7. Scientific work

Seminar “Photographic lighting and colour measurements”

8. Theses

- Calculation and design of MHD motors” (diploma thesis, 1982)

9. Main Areas of Scientific Work

- Analysis of the quality of street lighting and implementation of new measurement methods.

Date: 30.07.2008

APPENDIX C

ELULOOKIRJELDUS

1. Isikuandmed

Ees- ja perekonnanimi: Jelena Armas
Sünniaeg ja -koht: 15.09.1960, Tallinn
Kodakondsus: Eesti
Perekonnaseis: vallaline
Lapsed: tütar Aleksandra Armas-

2. Kontaktandmed

Aadress: Uus-Sadama 22-5, 10120, Tallinn
Telefon: (+372) 5107670
E-posti aadress: jarmas@hot.ee

3. Hariduskäik

Õppeasutus (nimetus lõpetamise ajal)	Lõpetamise aeg	Haridus (eriala/kraad)
Tallinna Tehnikaülikool	1982	tehnikateaduste magister, elektriajamid ja jõuelektroonika
Tallinna Tehnikaülikool	1982	diplomeeritud insener, elektriajamid
Tallinna 6. Keskkool	1979	põhiharidus

4. Keelteoskus (alg-, kesk- või kõrgtase)

Keel	Tase
Eesti	Kesktase
Inglise	Kesktase
Vene	Kõrgtase

5. Teenistuskäik

Töötamise aeg	Ülikooli, teadusasutuse või muu organisatsiooni nimetus	Ametikoht
1982 - 1985	Tallinna Tehnikaülikool	insener, nooremteadur
1985 - 1995	EKP KK Kirjastus (praegu Printall)	elektriinsener
1994 - 1996	AS Balti Ekspeditsioon	transpordijuht
1996 - 2001	AS Printall	energeetik
2001 - 2001	AS Keila Veskid	peaenergeetik
2002 - 2006	EA Reng AS	El.projekteerija
2006 -.	OÜ Jaotusvõrk	spetsialist

6. Täiendõpe

Õppimise aeg	Õppeasutuse või muu organisatsiooni nimetus
1998	OÜ Ohutusekspert “ Ehitiste madalpinge elektripaigaldiste eeskiri”
1999	International House “ Intermediate course in general English”
2000	E-Katedraal “Tuleohutusalaste täiendõpe”
2002	AS PE Konsultant “Kliendi mõjustamine
2006	Meta Profit “Toimetulek pingeliste kliendikontaktidega”
2008	Meta Profit “Stressijuhtimise ja pingevaba suhtlemise tehnoloogiad”

7. Teadustegevus

Seminaari koraldamine	“Pildistav valgustuse mõõtmine, värvuste mõõtmine”

8. Kaitstud lõputööd

- “Расчет и проектирование серии МГД - двигателей” (diplomitöö, 1982)

9. Teadustöö põhisuunad

- Tänavavalgustuse kvaliteedi analüüs ning uute mõõtmise meetodite juurutamine.

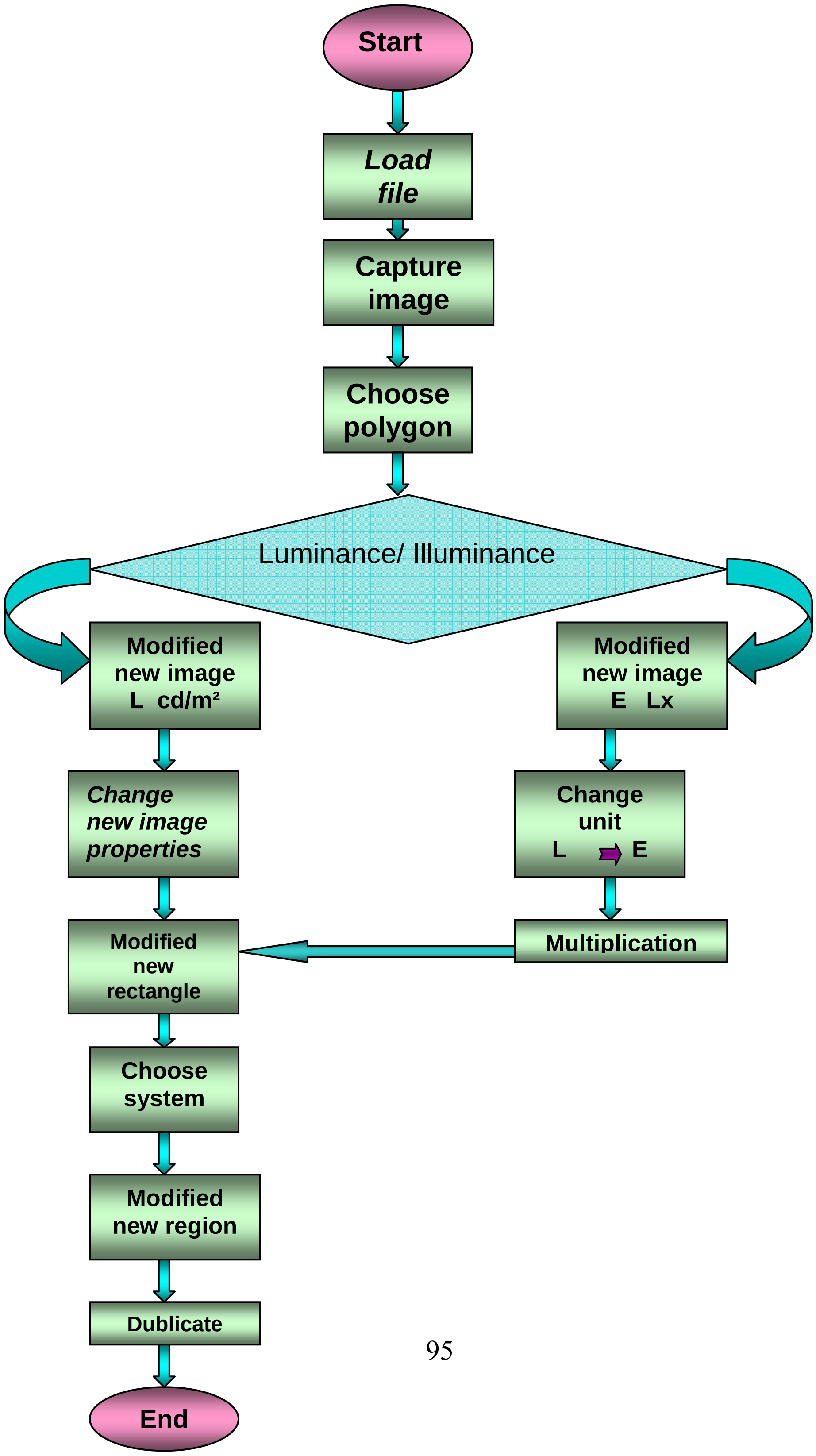
Kuupäev: 30.07.2008

DISSERTATIONS DEFENDED AT TALLINN UNIVERSITY OF TECHNOLOGY ON *POWER ENGINEERING, ELECTRICAL ENGINEERING, MINING ENGINEERING*

1. **Jaan Tehver**. Boiling on porous surface. 1992.
3. **Endel Risthein**. Electricity supply of industrial plants. 1993.
4. **Tõnu Trump**. Some new aspects of digital filtering. 1993.
5. **Vello Sarv**. Synthesis and design of power converters with reduced distortions using optimal energy exchange control. 1994.
6. **Ivan Klevtsov**. Strained condition diagnosis and fatigue life prediction for metals under cyclic temperature oscillations. 1994.
7. **Ants Meister**. Some phase-sensitive and spectral methods in biomedical engineering. 1994.
8. **Mati Meldorf**. Steady-state monitoring of power system. 1995.
9. **Jüri-Rivaldo Pastarus**. Large cavern stability in the Maardu granite deposit. 1996.
10. **Enn Velmre**. Modeling and simulation of bipolar semiconductor devices. 1996.
11. **Kalju Meigas**. Coherent photodetection with a laser. 1997.
12. **Andres Udal**. Development of numerical semiconductor device models and their application in device theory and design. 1998.
13. **Kuno Janson**. Paralleel- ja järjestikresonantsi parameetrilise vaheldumisega võrgusageduslik resonantsmuundur ja tema rakendamine. 2001.
14. **Jüri Joller**. Research and development of energy saving traction drives for trams. 2001.
15. **Ingo Valgma**. Geographical information system for oil shale mining - MGIS. 2002.
16. **Raik Jansikene**. Research, design and application of magneto-hydrodynamical (MHD) devices for automation of casting industry. 2003.
17. **Oleg Nikitin**. Optimization of the room-and-pillar mining technology for oil-shale mines. 2003.
18. **Taivo Kangilaski**. Eesti Energia käiduhaldussüsteem. 2004.
19. **Viktor Bolgov**. Load Current Stabilization and Suppression of Flicker in AC Arc Furnace Power Supply by Series-Connected Saturable Reactor. 2004.
20. **Raine Pajo**. Power System Stability Monitoring - an Approach of Electrical Load Modeling. 2004.
21. **Nikolai Dorovatovski**. Thermographic diagnostics of electrical equipment of Eesti Energia Ltd. 2004.
22. **Katrin Erg**. Groundwater Sulphate Content Changes in Estonian Underground Oil Shale Mines. 2005
23. **Argo Rosin.** Control, Supervision and Operation Diagnostics of Light Rail Electric Transport. 2005

24.

APPENDIX D
ALGORITHM



APPENDIX E

CD