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Report 51

INTELLIGENT ROAD LIGHTING CONTROL SYSTEMS --EXPERIENCES, MEASUREMENTS, AND LIGHTING CONTROL STRATEGIES

Liping Guo

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Abstract

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Abstract

The work starts with a brief overview of the main issues concerning road lighting control systems, e.g. the visual conditions in night time driving, the light sources used in road lighting, and the basic structure of telemanagement lighting control systems. Then the work focuses on the performance of intelligent road lighting control systems by using the examples of two installations in Finland, Ring III and VT7. The real benefits and drawbacks are discussed and financial calculations are given. The work continues with the subject of road surface luminance measurements in order to suggest ways in which the performance of intelligent road lighting control systems might be optimized. This subject is topical as there are currently several practical problems in luminance monitoring. The work also investigates the main control parameters and strategies that are applied currently and tries to find the basis of dynamically changing light levels.

Keywords Intelligent road lighting control, dimming, energy saving, luminance measurement

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Preface

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Many thanks go to the whole personnel of the Lighting Unit for the positive working atmosphere and to my friends in Finland for the priceless friendship.

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Liping Guo
Espoo, Finland, October 2008

Contents

List of publications

I. L. Guo, M. Eloholma, and L. Halonen (2008, January). Lighting control strategies for road lighting control systems, *the Journal of the Illuminating Engineering Society of North America (LEUKOS)* [Online], vol. 4, no. 3, 2008.
Available: http://www.iesna.org/leukos/Volume4/number3.cfm

II. L. Guo, M. Eloholma, and L. Halonen, "Intelligent road lighting control systems", Report 50, Department of Electronics, Lighting Unit, Helsinki University of Technology, Finland, 2008.

III. W. Chen, Z. Huang, L. Guo, Y. Lin, and D. Chen, "Performance of induction lamps and HPS lamps in road tunnel lighting", *Tunneling and underground space technology,* vol.23, issue 2, pp. 139-144, March 2008.

IV. L. Guo, M. Eloholma, and L. Halonen, "Intelligent road lighting control systems-overview and case study", *International Review of Electrical Engineering*, vol. 2, no. 1, pp. 14-20, January-February, 2007.

V. L. Guo, M. Eloholma, and L. Halonen, "Luminance monitoring and optimization of luminance metering in intelligent road lighting control systems", *Ingineria Iluminatului*, Vol. 9, pp. 24-40, 2007.

VI. A. Ekrias, L. Guo, M. Eloholma, and L. Halonen, "Intelligent road lighting control in varying weather conditions", *Light & Engineering*, vol. 16, no.1, pp. 72-78, 2008.

VII. A. Ekrias, L. Guo, M. Eloholma, and L. Halonen, "Intelligent road lighting and effects of weather conditions on road luminances", in *Proceedings of 26th session of the CIE*, *Beijing, China*, 2007, D4-108-109.

The author has played a major role in all aspects of the work presented in this thesis. She was the responsible author of publications I, II, IV and V. In publication III, the author participated in the measurement design and the analysis of measurement results and survey results. In publications VI and VII, she was responsible for the part concerning intelligent road lighting control systems.

List of abbreviations and symbols

ADT	Average Daily Traffic
AL	Lighting class for motor traffic in Tiehallinto (Finnish Road Administration) guidelines of road lighting design
ANSI	American National Standards Institute
CCD	Charge Coupled Device
CEN	Comité Européen de Normalisation
	European Committee for Standardization
CIE	Commission Internationale de l'Eclairage,
	International Commission on Illumination
EPA	United States Environmental Protection Agency
IESNA	Illuminating Engineering Society of North America
IEFL	Induction Electrodeless Fluorescent Lamp
ILE	Institution of Lighting Engineers
HID	High Intensity Discharge
HPS	High Pressure Sodium
ME	Lighting class for motor traffic in CEN standards
MH	Metal halide
NLPIP	National Lighting Product Information Program in the United States
LED	Light Emitting Diode
L_{av}	Average road surface luminance
$V(\lambda)$	Photopic spectral luminous efficiency function
$V'(\lambda)$	Scotopic spectral luminous efficiency function
VT7	Highway No. 7 in Finland

1. Introduction

1.1 Background

The electrical energy consumption of road lighting constitutes an important part of total energy consumption. Saving energy in road lighting is therefore important for total energy savings. It is known that road lighting levels are excessive in many cases. For instance, in the case of low traffic volumes, the lighting levels are excessive and could be reduced so that energy savings can be achieved [1]. On the other hand, in specific situations and for traffic safety reasons, light levels could be increased even in the case of low traffic volume. Telemanagement with networking and automation technology allows for control of individual lamps, adjustment of light levels, and instant lamp fault reports. In addition to the energy saving advantages, the adjustment of light levels can also contribute to the reduction of light pollution, while instant lamp fault reports can contribute to savings in maintenance and to increased safety [I].

Currently, the road lighting control systems range from very simple to the most modern applications. Different words are used to describe those lighting control systems, e.g. telemanagement, adaptive, dynamic and intelligent control systems. The names used are similar, nevertheless there are differences between them. The light levels in telemanagement lighting control systems can be adjusted adaptively, dynamically or intelligently. In the case when the light levels can be adjusted in real time or according to a predefined time schedule, the lighting system is called adaptive or dynamic. An adaptive or dynamic lighting control system can be intelligent when light levels are adjusted real time based on predefined parameters.

1.2 Objectives of the work

The first objective of the work is to analyze the performance of existing road lighting control systems.

As road surface luminance is one of the control parameters in intelligent road lighting control systems, the second objective is to optimize luminance metering as part of the control systems.

The final objective is to find the basis of, and suggest guidelines for, the dynamic changing of road lighting.

2. State of the art

In road and street lighting, luminances fall in the mesopic region. In Europe, the recommended average road surface luminances (L_{av}) are between 0.3 – 2 cd/m^2 and in the US between 0.3 – 1.2 cd/m^2 [2], [3]. It is known that neither V(λ) nor V'(λ) alone are representative of the eye's spectral sensitivity in the mesopic region. The spectral sensitivity of the eye at low light levels, or mesopic conditions, is determined by the rod and cone photoreceptors of the retina operating together in varying degrees as adaptation luminance shifts between the scotopic and photopic. Nevertheless, so far all lighting dimensioning is based on the photopic V(λ), which was established in 1924 [4].

The adoption of mesopic photometry will result in a different classification of light sources in terms of their luminous output. Light sources with high output in the short wavelength region have frequently been acknowledged to be visually more effective at the mesopic light levels [5]-[7], whereas the usage of photopic photometry at the low light levels of road and street lighting favours high pressure sodium (HPS) lamps because of their high output around the peak wavelength of the photopic $V(\lambda)$ [8].

At present, in roadway lighting applications, HPS and metal halide (MH) lamps are the most widely used light sources. In road tunnel lighting, fluorescent lamps and HPS lamps are widely applied. LEDs are fast developing light sources and are considered as one promising light source for general lighting. However, LEDs are not ready for road lighting applications, since the luminous output of LEDs is not high enough yet. Currently, HPS lamps are the dominant light source used in road lighting because of long lamp life time and high luminous efficacy. MH lamps offer high luminous efficacy and good colour rendering properties [9]. MH lamps compete with HPS lamps in road lighting as the whiter light of MH lamps provides better peripheral visibility at low illumination levels [10], [II].

Induction lamps are also employed in road and tunnel lighting applications where lamp maintenance is difficult. Induction electrodeless fluorescent lamps (IEFL) are fundamentally different from the traditional discharge lamps, which employ electrodes as the electron source. The operation frequency of IEFLs is usually in the range of hundreds of kHz to tens of MHz [11]. A special generator or ballast is needed to generate high frequency current and energizing coils are employed to generate an inductive electric field in order to sustain the gas discharge. Long life time and good lumen maintenance can be achieved because of the absence of electrodes. In road tunnel lighting applications, it has been shown that induction lamps provide higher luminous uniformity, better colour rendering, and lower maintenance costs than HPS lamps [III].

Traditionally, road lighting is switched on/off manually or automatically by photocells and/or timers. Lamps are burning at full power during the whole night and lighting intensity is often excessive when traffic density is low or the road surface is covered with snow [12]. In some cases, every second luminaire is switched off in order to save energy. However, this results in poor luminance uniformity and therefore poor driving conditions. With dimming technology, these disadvantages can be avoided [13].

Although the current telemanagement road lighting control systems range from rather simple to very intelligent applications, the basic structures are similar. A telemanagement road lighting control system consists of a control centre, remote terminal units, light control units, ballasts, and lamps [1], [14]-[16]. The main functions of the control centre are monitoring the lamp operation, making decisions according to control parameters and saving the operation data. Remote terminal units are installed in the control cabinets of the installations. A control cabinet normally contains several lighting contactors, circuit breakers, a timer and/or a photocell. Remote terminal units can collect lamp information from light control units and send the information to the control centre, receive the commands from the control centre and transmit them to light control units. Light control units receive commands from the remote terminal units, execute the command, and transmit the status information of the lamps to the remote terminal unit [1], [14]-[16]. In intelligent road lighting control systems, the control centre is normally connected to the traffic control centre and illuminance/luminance meters so that the light levels can be adjusted based on the information of traffic density, road surface conditions and measured illuminance/luminance levels.

One of the forerunners in the field of intelligent road lighting control is the Netherlands, where studies of dynamic changing of public lighting were started in 1990s [17]. In the Netherlands, a pilot dynamic roadway lighting system was installed in the late 1990s to examine under which circumstances, which lighting levels can be applied with respect to driving behaviour, safety and perception [17]. The pilot installation can be operated at three luminance levels, depending on the amount of traffic and weather conditions. The lighting control system operates at 20%, 100%, and 200% of normal lighting levels on a 14 km six-lane highway; the luminance levels are 0.2 cd/m^2, 1.0 cd/m^2, and 2.0 cd/m^2, respectively. No negative safety effects at the 20% light level were found and it was concluded that 20% of light level is sufficient for low traffic volume at night provided the weather is fine. At the other end of the scale, the costs of a 200% light level were high but the safety benefits were marginal or unmeasurable [IV]. Based on the findings, currently new lighting installations in the Netherlands must be dimmable, based on traffic volume or time schedule.

Norwegians have been very active in promoting dynamic road lighting control systems. Several telemangement lighting control systems based on a time schedule have been installed in Norway since 2002 and further study is still underway [12].

The EU project *E-street* has been playing an active role in increasing knowledge and awareness of intelligent road lighting and in accelerating the use of these technologies in Europe since the project start at the beginning of 2005 [18].

In North America, several installations of telemanagement road lighting control systems with time-schedule dimming were built after 2000 and there will be more installations in the coming years. These installations, enabled by developments in technology, are for the purpose of energy savings [16], [IV].

In China, the number of road lighting installations has dramatically increased during the last few decades with the construction of roads and streets. At the same time, more attention has been paid to energy savings through increased energy-efficiency of road lighting. Telemanagement road lighting control systems based on a time schedule have become more widely used in China since 2000 [19], [IV].

In Finland, several intelligent road lighting control systems have been installed; these are on motorway VT1, Ring III, VT7, and Vuosaari. The control systems were designed and built by different companies. The performance of two existing systems, Ring III and VT7, is analyzed in this work. However, this work was not concerned with the design or implementation of the control systems.

So far, there are no internationally accepted guidelines concerning dynamic changing of light levels in road lighting. The dimming strategies are made on the basis of experiences of lighting designers.

3. Road lighting control system analysis

In Finland, several intelligent road lighting control systems have been installed in order to get energy savings and to reduce maintenance costs. The performance of two Finnish installations, Ring III and VT7, are investigated and compared [II].

3.1 System descriptions of Ring III and VT7

An intelligent road lighting control system was installed in Finland on Helsinki Ring III in autumn 2005. The control system has been in use since January 2006. There are altogether 492 luminaires with 600W high pressure sodium lamps on the 4 km six-lane road between Lentoasemantie-Tikkurila. The lighting class of Ring III is AL2 with average road surface luminance 1.5 cd/m^2 [20]. The requirements of lighting class AL2 are the same as that of ME2 in CEN standards except for the longitudinal uniformity [3].

Another similar lighting control system was installed on the Helsinki-Porvoo motorway (VT7) between sections Västersundom and Harabacka at the end of 2006 and has been in use since January 2007. 150W, 250W and 400W HPS lamps are installed on the 31 km four-lane road. The lighting class of VT7 is AL3 with average road surface luminance 1.0 cd/m^2. AL3 are corresponding to ME3 in CEN standards. In order to achieve more energy savings and adjust the light levels according to real needs, the luminaires in the two driving directions are controlled separately on VT7, since there are substantial differences in traffic density between the two driving directions during rush hours.

The infrastructure of the two control systems is quite similar. The control centre of Finnish Road Administration in Pasila collects and analyzes traffic volume, road surface luminance, and road surface conditions data as shown in Fig. 1, and makes decisions relating to dimming by comparing the data with the predefined parameters. The commands are transmitted through telephone lines and a power line carrier to light control units to dim the lamps. The measured road surface luminance level is the average value of recordings of every 10 minutes. The traffic volume is the total number of vehicles over a period of 5 minutes for all the six lanes of Ring III and for each carriageway (two lanes) of VT7. Road surface conditions used are wet or dry road surface.

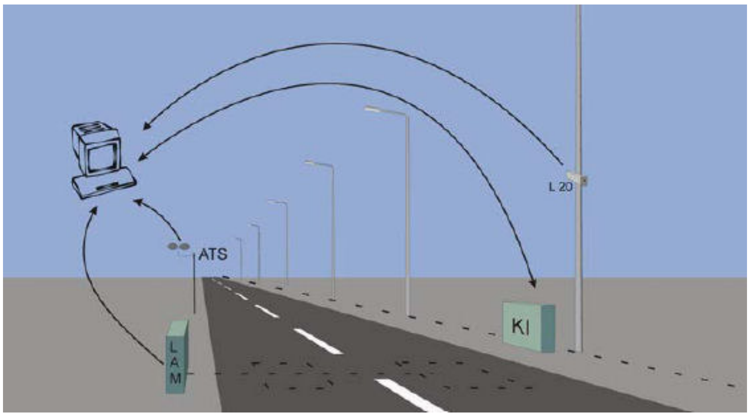


Figure 1 - Information source devices on Ring III and VT7, (ATS – road weather station, LAM – traffic monitoring system, L20 – luminance meter, KI – electrical distribution box).

In both systems, electromagnetic ballasts are employed and the controlling method is voltage dimming by triac. Figure 2 illustrates the typical dimming characteristics of HPS lamps installed on Ring III and VT7. Although different wattages of HPS lamps are applied on Ring III and VT7, the lamp dimming characteristics are essentially the same. The HPS lamps can be dimmed down to 20% of light output and to 35% of rated power. In both Ring III and VT7 installations, the dimming range is set from 40% to 100% of rated power.

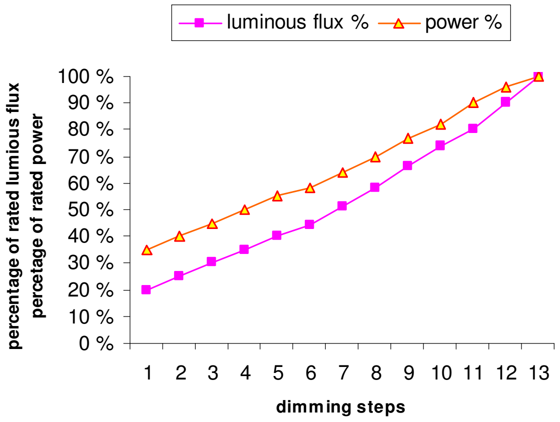


Figure 2 - Typical dimming characteristics of HPS lamps [II]

Both on Ring III and VT7, the status of lamps are monitored in the control systems. The systems can detect lamp defects as damaged lamp, blinking lamp, and link defect (power line cut). The control centre can locate fault lamps and send maintenance workers to fix or replace them immediately if they are in critical locations.

The structure and components of the road lighting control systems on Ring III and VT7 are essentially the same, except for the definition of control parameters and the separate control of luminaires in the two directions of VT7. The control parameters of Ring III and VT7 are shown in Tables 1 and 2. The values are defined based on experience of road lighting designers. Road surface luminance values are collected by the luminance meters and used as feedback to finally adjust the light levels. The purpose of monitoring road surface conditions is to avoid decreasing road surface luminance further in wet conditions. However, the measured road surface luminance values in different road surface conditions are not reliable due to communication problems. Information of road surface conditions from the weather stations are not used either due to technical problems. Currently, traffic volume is the only functioning parameter in the lighting control systems of Ring III and VT7.

Table 1 - Control parameters for Ring III

Vehicles per 5 minutes	Luminance (cd/m^2)	Lamp power (%)
1	0.75	40
10	0.80	45
20	0.85	50
35	0.95	55
40	1.00	60
50	1.02	65
60	1.05	70
70	1.10	75
80	1.15	80
90	1.20	85
100	1.30	90
150	1.40	95
170	1.50	100

Note: The number of vehicles per 5 minutes is collected from all six lanes.

Table 2 - Control parameters on VT7

Vehicles per 5minutes	Luminance (cd/m^2)	Lamp Power (%)
24 or less	0.25	40
25 – 69	0.50	60
70 -99	0.70	80
Over 100	1.00	100

Note: The luminaires in two driving directions, from Helsinki to Porvoo and from Porvoo to Helsinki, are controlled separately according to traffic volume per driving direction. The number of vehicles per 5 minutes is collected for each direction.

According to Table 1, the control system of Ring III is based on continuous dimming with 5% dimming steps, and there is a required minimum luminance value for each dimming level. The minimum luminance is 0.75 cd/m^2 when the lamps are dimmed to 40% of rated power. However, based on the dimming characteristics in Fig. 2, when the lamps are dimmed to 40% of rated power, the light output is 25% of initial light output. Suppose that the average road surface luminance is 0.75 cd/m^2 when lamps are burning at 40% of rated power, the road surface luminance will be as high as 3 cd/m^2 when lamps are burning at full power, which is much higher than the requirement of lighting class AL2. The values of luminance requirements given in Table 1 are actually not correct.

In Table 2, the dimming levels of VT7 are based on the dimming characteristics of HPS lamps. The major differences between Ring III and VT7 lie in the number of dimming levels and in the separate control of luminaires in the two driving directions of VT7. On Ring III, lamp power is adjusted with 5% steps with the traffic volume as defined in Table 1. When the traffic volume is below 100 vehicles per 5 minutes, the lamp power is very sensitive to the change in traffic volume; for example, even a 5-vehicle change in 5 minutes can result in 5% variation in lamp power. On motorways like Ring III, traffic volume changes all the time and the power of the lamps is consequently adjusted all the time. However, on VT7, there are only four dimming levels. The lamps can operate stably at a particular power level for a relatively long period.

3.2 Data analysis

The intelligent road lighting control systems in Finland are so new that there is lack of experience, which has led to cooperation problems between companies involved in the design and implementation of the control systems.

There have been communication problems between the control cabinets and the control centre. For instance, the control cabinets send information to the control centre but cannot receive commands from the control system. The lamps are switched on/off automatically by the photocells and burn at 100% of rated power if there are communication problems. The information in the control centre, such as the switch on/off times, traffic volumes and road surface conditions, is reliable, except for the lamp dimming levels. However, lamps are not dimmed when the control cabinets do not receive dimming commands due to communication problems. The average power and the energy consumption calculations presented in the following chapters are based on the ideal case when the communication systems have been working properly throughout the whole year. The real savings of electricity are not as great as those in the calculations.

3.2.1 Installation on Ring III

The data from the control centre has been analyzed for Ring III for the whole of year 2006. Figure 3 illustrates the average daily energy consumption of each luminaire (600 W HPS lamp) per month from January to December 2006. It is obvious that the energy consumption in June is the lowest due to the long duration of daylight. January, November and December have the highest energy consumption because of the darkness in winter time. Figure 4 shows the average number of daily burning hours and average lamp power per month. The average number of daily burning hours in June is only 3.7 hours, while in December it is 17.5 hours. The average number of daily burning hours follows the same trend as average monthly energy consumption, but the average power does not have an obvious trend, as the lamp power is mainly decided by traffic flow, which does not vary significantly between months. Figure 5 indicates that the average power per month is between 50% and 60% of rated power. The annual number of lamp burning hours is 3850, calculated from the switch on/off times collected in the control centre. Since the power consumption of the control components is very small, e.g. only two or three watts for each light control unit or remote terminal unit, this part of electricity consumption is omitted from the energy costs calculations. By assuming that the annual average lamp power is 55% of rated power in the ideal case and that lamp ballasts consume 10% of rated lamp power, the energy saving for a 600W HPS lamp will be about 40.9% compared to traditional lighting systems installed with the same kinds of lamps [II].

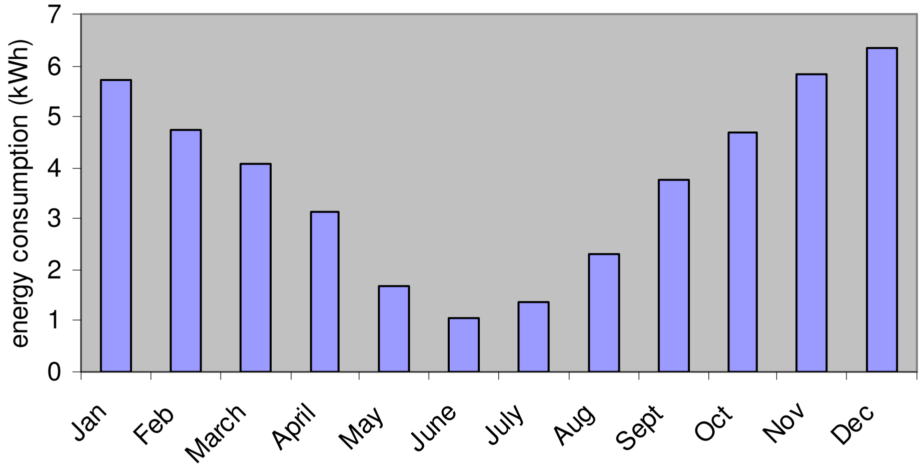


Figure 3 - Average daily energy consumption per luminaire per month on Ring III in Finland.

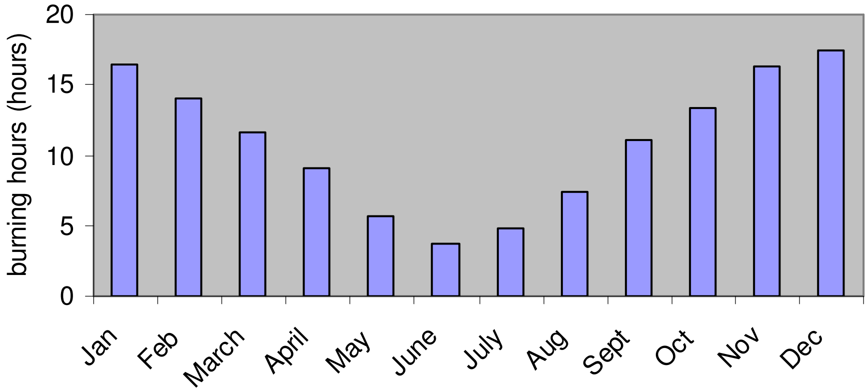


Figure 4 - Average number of daily burning hours per month on Ring III in Finland.

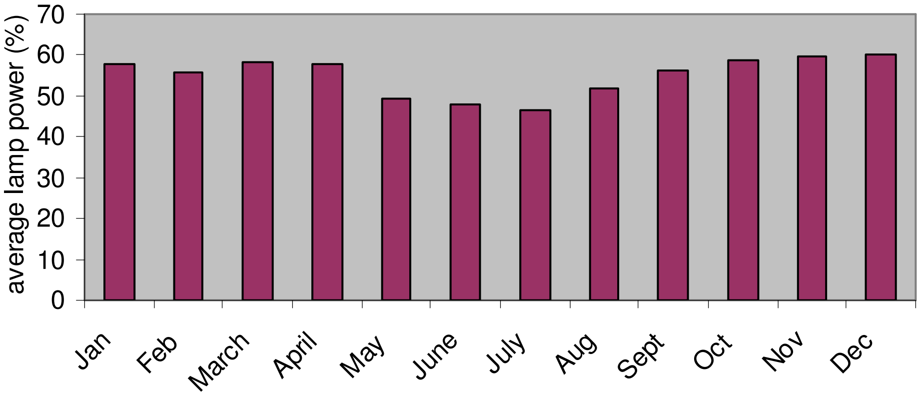


Figure 5 - Average lamp power per month on Ring III in Finland.

3.2.2 Installation on VT7

The major differences between Ring III and VT7 installations lie in the number of dimming levels and in the separate control of luminaires in the two driving directions of VT7. The data from the control centre has been analyzed for VT7 for the whole of year 2007. The daily average number of burning hours each month (except April 2007, due to missing data in that month) for VT7 are shown in Fig. 6. As both systems are switched on/off by photocells and as they are located at similar latitude and longitude, the switch on/off time and burning hours are almost the same on Ring III and VT7 each month. In June, the average number of daily burning hours is less than 4 hours per day, whereas, in December, they are more than 17 hours per day.

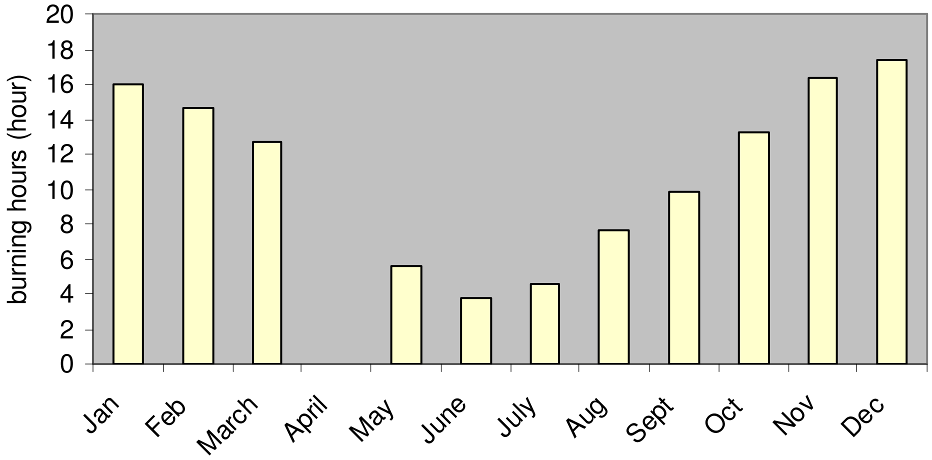


Figure 6 - Average number of daily burning hours per month on VT7 in Finland

Figure 7 shows the average lamp power per month for VT7 according to the data collected in the control centre. Due to different values in control parameters and different trends in traffic volume, the average lamp power is lower on VT7. In the ideal case when the communication systems work properly throughout the whole year, on Ring III, the average lamp power is between 50% and 60% of rated power, whereas, on VT7, the average lamp power is between 40% and 50% of rated power. On VT7, there is no significant difference in the average lamp power between the two driving directions.

Figure 8 illustrates the average daily energy consumption per luminaire (for a 250W HPS lamp) per month on VT7, for both driving directions, i.e. from Helsinki to Porvoo and from Porvoo to Helsinki. Both on Ring III and VT7, the average energy consumption follows the same trend as average number of daily burning hours, e.g. in June and July, the energy consumption is the lowest and in January, November and December, the energy consumption is the highest. On VT7, there is no significant difference in the energy consumption of luminaires between the two driving directions.

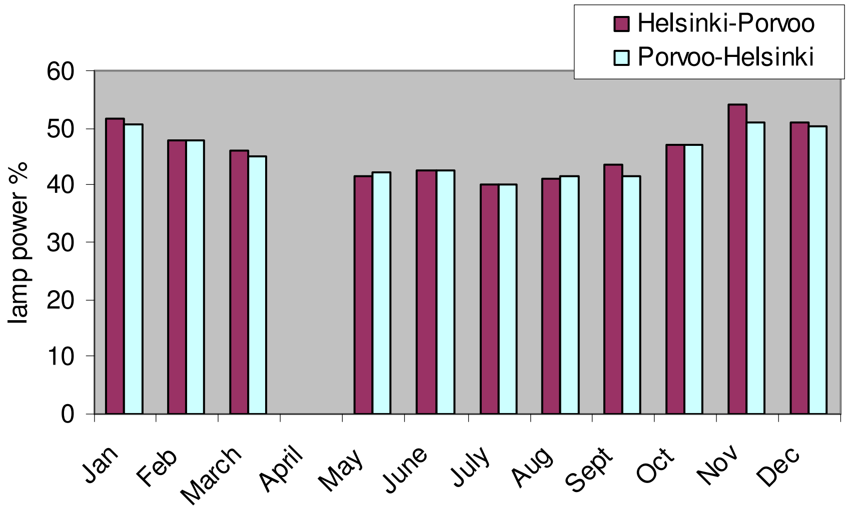


Figure 7 - Average power (in percentage of rated power) per month on VT7 in Finland

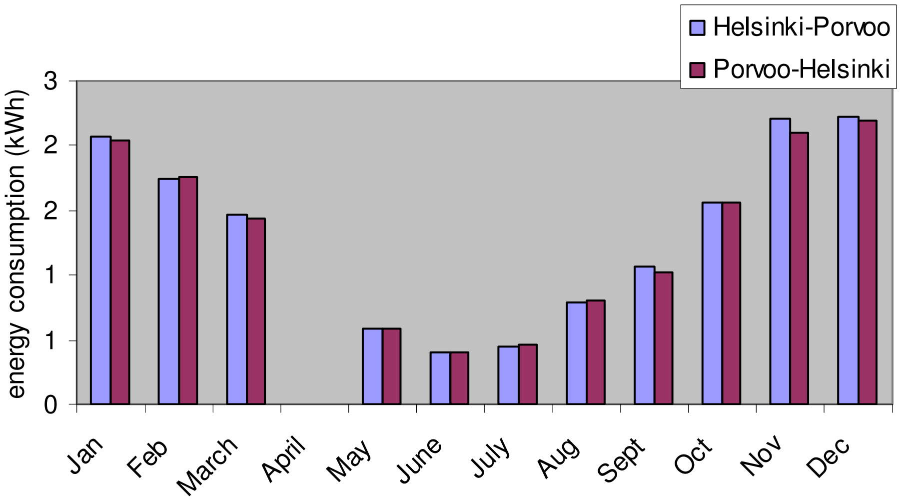


Figure 8 - Average daily energy consumption per luminaire per month on VT7 in Finland

The initial purpose of the separate control of luminaires on VT7 in the two driving directions was to save more energy and to provide light levels appropriate for the actual needs, as there are substantial differences in traffic density in rush hours for the two driving directions. In the morning, there are more cars travelling in the Porvoo-Helsinki direction and in the afternoon more travelling in the Helsinki-Porvoo direction. Figure 9 shows the traffic volume curves of the two driving directions of VT7 on one weekday (2007.02.12, Monday). Figure 10 illustrates the traffic volume curves for the two weeks from 2007.01.22 (Monday) to 2007.02.04 (Sunday) [I].

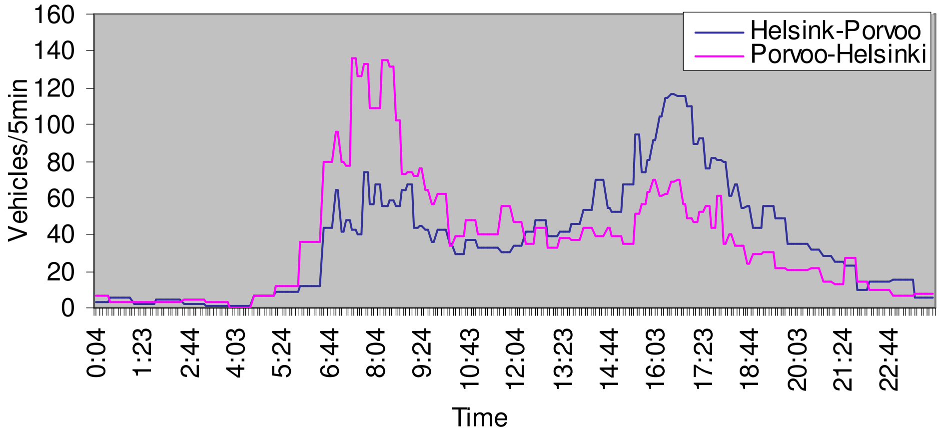


Figure 9 - Traffic volumes in the two driving directions of VT7 on Monday February 12, 2007

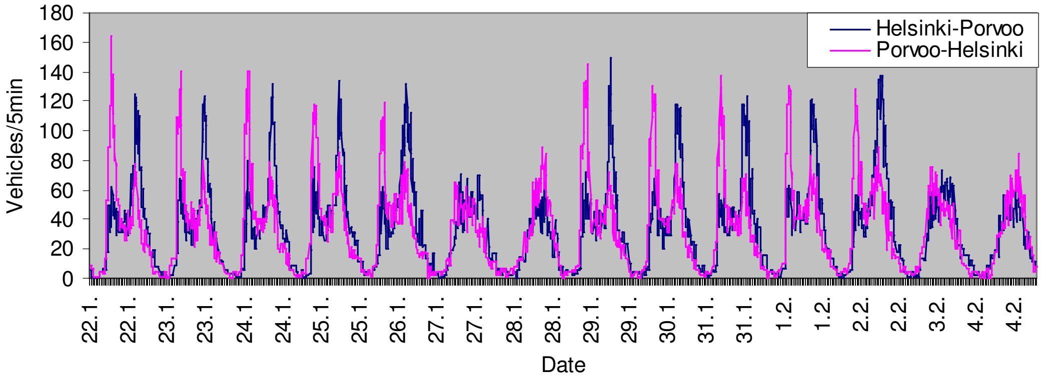


Figure 10 - Traffic volumes in the two driving directions of VT7 during the two weeks from 2007.01.22 (Monday) to 2007.02.04 (Sunday)

The traffic volumes indicate that additional energy savings from the separate control of the luminaires in the two driving directions are gained mainly during rush hours from 6:30 to 9:00 and from 15:30 to 18:00 on working days during winter. The differences in traffic volume in the two driving directions result in a maximum of 40% difference in lamp power of the two luminaire groups during rush hours. For example, in the morning, the power of lamps in the Helsinki-Porvoo direction is at 80% (or 60%) of rated power, whereas, in the Porvoo-Helsinki direction, the lamp power is at 100% (or 80%), and in the evening vice versa.

Table 3 shows the average lamp switch on/off times and burning hours for each month on Ring III in 2006. For VT7, the switch on/off times are similar to Ring III every year as the on/off switch mechanisms of the two systems are the same and both systems are located at similar latitudes and longitudes. The annual number of lamp-burning hours is around 3850 on both VT7 and Ring III. The annual number of burning hours during morning rush time are 234.8, corresponding to the time when the luminaires in Helsinki-Porvoo direction are burning at lower power than in the other direction. The annual number of burning hours during evening rush time is 116.4, corresponding to the time when luminaires in the Porvoo-Helsinki direction are burning at lower power. In the calculation of additional energy savings, it is assumed that the difference in lamp power during rush hours is 40% of rated power between the luminaires in two directions, with which the maximum additional savings can be calculated for each driving direction.

Table 3 - Average lamp switch on/off times and burning hours on Ring III in 2006

Month	Average switch on time	Average number of daily burning hours in evening rush hours	Average switch off time	Average number of daily burning hours in morning rush hours	Number of working days	Sum of burning hours in rush time
January	16:31	1.50	8:57	2.50	21	84
February	17:46	0.25	7:52	1.50	20	35
March	19:04	0	6:45	0.25	23	5.75
April	21:07	0	6:11	0	17	0
May	22:51	0	4:31	0	21	0
June	23:56	0	3:39	0	22	0
July	23:37	0	4:11	0	21	0
August	22:03	0	5:23	0	23	0
September	20:34	0	7:40	1.17	21	24.57
October	18:52	0	8:00	1.50	22	33
November	16:16	1.75	8:33	2.00	22	82.5
December	15:42	2.30	9:13	2.50	18	86.4
Sum hours/year	116.4		234.8		351.2	

By using the same switch on/off times as on Ring III (Table 3) and assuming that the ballast losses are constant in dimming, the maximum additional yearly energy savings for a 250W HPS lamp (274 W for luminaire) on VT7 from the separate control can be calculated roughly as follows:

The total energy consumption of each luminaire without control would be
274W*3850 hours= 1054.9 kWh/year

If there were no separate control on VT7, assuming the annual average lamp power is 50% of the rated power, the energy savings would be
250W*50%*3850 hours = 481.3 kWh/year
Savings in percentage
481.3 kWh / 1054.9 kWh= 45.6 %

With a separate control for each of the two driving directions, for each luminaire in the Helsinki-Porvoo direction the additional energy savings would be
250W * 40 % * 234.8 hours = 23.4 kWh/year
Total savings with separate control
23.4 kWh + 481.3 kWh = 504.7 kWh/year
In percentage terms compared to the energy consumption without control
Additional savings 23.4 kWh / 1054.9 kWh ≈ 2.2 %
Total savings 504.7 kWh / 1054.9 kWh ≈ 47.8 %

With a separate control for each of the two driving directions, for each luminaire in Porvoo-Helsinki direction, the energy savings would be
250W*40%*116.4 hours=11.6 kWh/year
Total savings with separate control
11.6 kWh + 481.3 kWh = 492.9 kWh
In percentage terms compared to the energy consumption without control

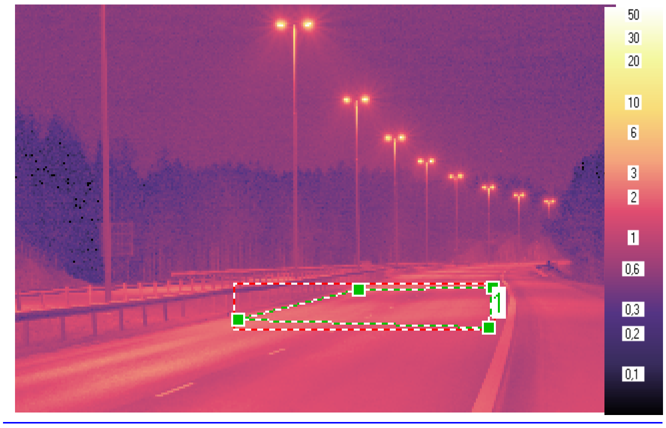
Additional savings 11.6 kWh / 1054.9 kWh ≈ 1.1 %
Total savings 492.9 kWh / 1054.9 kWh ≈ 46.7 %

The calculation indicates that the additional energy savings from the separate control of luminaires per of the two driving directions are small; for example, without separate control, the energy savings would be as much as 45.6% compared to the case without separate control, whereas, with separate control, there would be only 2.2 % additional savings at most for luminaires in the Helsinki-Porvoo direction and 1.1% at most for luminaires in the Porvoo-Helsinki direction. The control system with separate control is more complicated due to doubled data transmission and dimming level calculations compared to that without separate control. Therefore, benefits from separate control are not obvious.

3.3 Road lighting measurements on Ring III and VT7

Road luminance measurements were taken on Ring III and VT7 according to the European standard EN 13201-3 [21], except for the observer locations. On Ring III, the observer took the measurements on a bridge while, on VT7, the observer was on the side of the road. The measurements were made in March and April between 11pm and 1am when the road surface was dry. The lamp power was adjusted to 100% of rated power on both Ring III and VT7 in the measurements. All measurements were made using the imaging luminance meter LMK Mobile Advanced and analyzed by computer program LMK 2000. The system accuracy is ±8.2%.

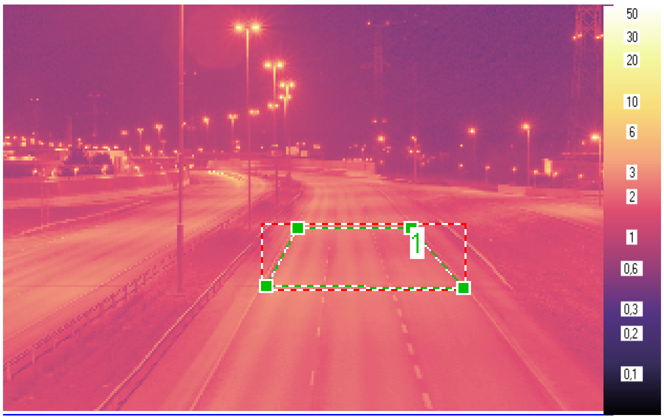
Results of the road luminance measurements on Ring III and VT7 are presented in Figs. 11 and 12, in which the lamps are shown burning at 100% of rated power and the road surface is dry. For each measurement, the average luminance L_{av}, overall uniformity U_0, and longitudinal uniformities for each lane ($U_{L,left}$, $U_{L,right}$, $U_{L,middle}$) were calculated as defined in EN 13201-3.



$L_{av} = 1.42\ cd/m^2$, $U_0 = 0.47$

$U_{L,left} = 0.42$, $U_{L,right} = 0.38$

Figure 11 - Luminance distributions measured on VT7 in Finland. The road section is lit with 250W HPS lamps. Average luminance L_{av}, overall luminance uniformity U_0, and longitudinal luminance uniformities for the left $U_{L,left}$, and right $U_{L,right}$ lanes.



$L_{av} = 2.39\ cd/m^2$, $U_0 = 0.53$

$U_{L,left} = 0.59$, $U_{L,middle} = 0.65$, $U_{L,right} = 0.61$

Figure 12 - Luminance distributions measured on Ring III in Finland. The road section is lit with 600W HPS lamps. Average luminance L_{av}, overall luminance uniformity U_0, and longitudinal luminance uniformities for the left $U_{L,left}$, middle $U_{L,middle}$, and right $U_{L,right}$ lanes.

Figures 11 and 12 indicate that, when the lamps are burning at 100% of rated power, the average road luminance on Ring III is 60% higher than the requirement of lighting class AL2 and, on VT7, 42% higher than AL3 [20]. The intelligent road lighting control system on Ring III had been in use for more than two years and on VT7 for more than one year when the measurements were undertaken. Since the light output of HPS lamps depreciate with age, the initial average road surface luminances on Ring III and VT7 were even higher. The lamp power is actually over-dimensioned both on Ring III and VT7. The energy saving costs calculations for Ring III and VT7 are based on the assumption that the design of the traditional systems is the same as the intelligent systems, e.g. the same kinds and number of lamps, the same height of light poles and the same luminaire spacing. However, if the lamp power is over dimensioned, the energy savings are not as much as those in the calculations.

In Ring III and VT7 installations, the dimming range is set from 40% to 100% of rated power. The road surface luminance at different dimming levels corresponding to the measured luminances can be calculated for Ring III and VT7. Table 4 lists the calculated road surface luminances at seven dimming levels and with 10% of dimming step. The luminous efficacy decreases greatly with dimming, e.g. when the HPS lamps are burning at 40% of rated power, the luminous efficacy is only 62.5% of the luminous efficacy when the lamps are burning at full power. Based on the dimming characteristics of HPS lamps and manufactures' suggestion, it is suggested that the maximum recommended dimming level for HPS lamps is 50% of rated power, at which the shift in colour rendering, colour temperature, light output and luminous efficacy are acceptable.

Table 4 - Dimming characteristics of HPS lamps and road surface luminances at different dimming levels corresponding to the measured luminances on Ring III and VT7

Lamp power	Light output	Ring III Luminance (cd/m^2)	VT7 Luminance (cd/m^2)	Luminous efficacy
40%	25%	0.60	0.36	62.5%
50%	35%	0.84	0.50	70.0%
60%	50%	1.20	0.71	83.3%
70%	59%	1.41	0.84	84.3%
80%	70%	1.67	0.99	87.5%
90%	80%	1.91	1.14	88.9%
100%	100%	2.39	1.42	100%

3.4 Road lighting maintenance

The maintenance cost is a significant part in the life cycle cost of road lighting. How to reduce maintenance cost is one of the major considerations for both traditional and intelligent lighting systems. One of the initial motivations for intelligent road lighting control is that the maintenance costs are expected to be reduced. Since the lamp status is monitored in the control centre, the system can detect and locate the lamp fault instantly, enabling the patrol frequency to be reduced and the response time to be shortened. However, it should be remembered that intelligent road lighting control systems are still very new and that not much experience in their maintenance has yet been accumulated [II].

Like traditional lighting systems, the efficiency of intelligent road lighting systems decreases over time due to light losses. There are several factors causing light losses: lamp lumen depreciation, lamp and ballast failure, dirt accumulation on lamps and luminaires, luminaire surface deterioration and damaged light poles. In combination, these factors commonly reduce light output by 20-60% [22]. Proper maintenance then becomes essential to the reliability and continued high performance of the roadway lighting system.

Due to the cost of labour, relamping is a particularly expensive component of lighting system maintenance. There are two relamping techniques, spot relamping and group relamping.

Spot relamping is the procedure of replacing a lamp when it has failed. The response times to replace a failed or cycling lamp should be established. Traditionally, owners patrol a lighting system on a scheduled basis and replace lamps as necessary. Many cities and utilities depend upon police reports and citizen call-ins to locate outages [23]. With an intelligent road lighting system, patrol frequency can be reduced, since lamp and ballast information are monitored real time and the lamp failure can be detected and alarmed instantly by the control system.

Group relamping is the procedure where all lamps are periodically replaced on a “best time schedule”. The “best time schedule” is when the total cost of installation, energy use, and relamping is at its minimum. For many installations, a group relamp conducted at 2/3 to 3/4 of the rated lamp life provides the mix of minimum acceptable light levels and limited outages yielding the lowest cost [23]. With intelligent road lighting, the group relamping can be well planned on the basis of comprehensive lamp information, which ensures good lighting quality and driving safety.

The intelligent road lighting installation of Ring III has been in use for over two years and that of VT7 for over one year. The construction companies are responsible for the maintenance of the lighting systems of Ring III for the first three years and of VT7 for the first five years. Afterwards, other maintenance companies will be in charge. Until now, there is not enough information to calculate the maintenance costs for Ring III and VT7 installations.

Both on Ring III and VT7, the status of lamps are monitored by the control systems. The control centre can detect different types of lamp faults, locate the fault lamps and send maintenance workers to fix or replace the fault lamps immediately if they are in critical locations.

As the intelligent road lighting control systems are so new and as there are many new components, road lighting maintenance companies do not have enough knowledge and experience with which to carry out maintenance. It is expected that an IT person/company is required to be responsible for the maintenance of software and databases, and for giving instructions and supervision to road lighting maintenance companies. Training courses should be organized occasionally for the maintenance workers as well.

The IT person/company and the road lighting maintenance companies should together be responsible for the maintenance of control units, luminaires, and luminance meters. For the maintenance of luminance meters, the cleaning of lenses should be conducted annually. Changes in surroundings may affect the average road surface luminance values measured by the luminance meters. For example, light from new buildings may result in higher road surface luminance. Thus placement of the luminance meters should be adjusted accordingly in order to provide proper readings.

As to the weather stations and traffic volume detectors, the maintenance work is conducted by other professional companies, and is not considered as part of the road lighting maintenance on Ring III and VT7.

3.5 Financial calculations

As discussed above, the main purpose of intelligent road lighting control systems is to save energy. In practice, it is important to make economic calculations to make sure the project is cost-effective. In the road lighting field, payback period and life cycle cost are two calculation methods commonly used [24]. For intelligent road lighting control systems, the main savings result from reduced energy consumption and expected reduction of maintenance costs. The payback period is then an option for economic calculations to show how many years the installation will pay itself back with the savings. However, the payback period does not properly account for time, value of money, risk, inflation, financing or other important considerations. Life cycle cost analysis calculates the cost of a system or a product over its entire life span. It is widely used in new product development studies, project evaluations and management accounting. The financial calculations of many of the large road construction projects are based on the method of life cycle costs [24]. This method is useful also in calculating the costs of road lighting installations. Although significant energy savings can be achieved from intelligent road lighting control systems, the initial construction costs are higher than for traditional road lighting. It will be of great interest to calculate life cycle costs for intelligent road lighting control systems. However, it is not possible to make life cycle cost calculations for Ring III and VT7 systems at the moment, since the operation times are still short and there are new electronic components whose life cycles are not known yet.

Table 5 compares the construction costs of the intelligent road lighting control system of VT7 with a traditional road lighting system. It is assumed that the traditional road lighting system has the same numbers and types of luminaries, foundations, columns, and earth cables as the intelligent road lighting control system.

Table 5 - A comparison of the construction costs of the intelligent road lighting control system of VT7 and a traditional road lighting system [II]

	Intelligent control system	Traditional system
Item	Cost in percentage compared to the total cost of the traditional system (%)	Percentage of total costs (%)
Foundations	18.3	18.3
Columns	26.0	26.0
Luminaires (including light control units)	18.5	9.9
Cables	10.2	10.2
Cabinets	1.7	0.4
Control system (including planning, database, software, training, luminance meters)	6.1	0
Earth work	32.5	32.5
Demolition	2.8	2.8
	116.1	100

The initial investment costs of the intelligent road lighting control system are 16.1% higher than those of the traditional road lighting system. The costs of cabinets, the control system (including planning, database, software, training are luminance meters), and luminaires in the intelligent lighting system are much higher than those in the traditional system, e.g. the cost of luminaires in the intelligent system is 87% higher than that in the traditional system, and the cost of cabinets is 325% higher. However, those items do not represent a major part of the total costs. In the traditional system, the costs of luminaires and cabinets represent 10.3% of the total costs, and, in the intelligent system, the luminaires and cabinets are 22.7% of the total costs. The costs of foundations, columns and earth work represent the most important part of the total construction costs.

In the following, the payback period for the intelligent road lighting control system of VT7 is calculated assuming that energy savings are 45% and there are no savings from the maintenance costs.

Total power

368.64 kW

Total energy consumption at 100% power each year

368.64 kW * 3850 h = 1419264 kWh/a

45% of energy saving

1419264 kWh/a * 0.45 = 638668.8 kWh/a

Savings from electricity (electricity price 0.09 €/kWh)

638668.8 kWh/a * 0.09 €/kWh = 57480.19 €

Payback period

difference in construction costs / savings from electricity ≈ 7 years

In the payback period calculations, 0.09 €/kWh is used as the price of electricity. If the electricity price is lower or the energy saving is less, the payback period will be longer and vice versa. The calculations show that, in case of no savings from maintenance costs, the installation can pay for itself in seven years with savings from electricity, although the construction cost of the intelligent road lighting system is higher than the traditional lighting system. However, in practice the construction costs, maintenance costs and electricity prices vary in different countries. The real payback periods vary in different cases. Nevertheless, the payback period calculation above is an indication to show the possible benefit of intelligent road lighting control systems.

3.6 Discussion

It is known that, when traffic volume is low or when the road is covered with snow, road surface luminance levels may be excessive and could be reduced [1]. When planning a new lighting installation, a maintenance factor is taken into account due to the lamp lumen depreciation. Therefore, depending on the lamp type, a new installation or an existing installation right after relamping may produce up to 20 % of light excess. It is possible to eliminate this effect by dimming based on the actual lamp output to correct for this gradual reduction of light flux during the lamp life [25].

The luminance method is mainly used as a method in road lighting design and evaluation of lighting quality. It is reasonable to introduce road surface luminance as one of the control parameters in detecting the variations in road surface luminance and maintain certain light levels whenever the lamps are new or aged. However, there are several practical problems in monitoring road surface luminance in different road surface conditions; these are discussed in the next chapter.

Currently, there are no guidelines specifying which control parameters should be used, and how the dimming levels should be defined.

Traffic volume information can be collected by inductive loops underground or by traffic cameras. It is possible to get the traffic volumes for each lane, for the lanes in the same direction or for all the lanes. In the case of VT7, the additional savings from separate control of luminaires in the two driving directions are small. For ease of use, traffic volume in all lanes is recommended as the main parameter to determine the dimming levels. Since the pattern of traffic volume varies in different situations, it is very difficult to give a general definition of high, medium or low traffic volume for all cases. Therefore, the traffic volumes for different dimming levels should be determined after carefully analyzing the patterns of traffic volume per case.

There is a common problem in the intelligent road lighting control systems on Ring III and VT7, which is the delay in adjusting light levels due to the data collection and transmission, and the time needed for a smooth change of dimming levels (5% of power reduction every 2 minutes) [14]. The time delay will result in unnecessarily high light levels, or too low light levels in some cases. As discussed before, there are general trends in traffic volumes for VT7; for example, the traffic volumes on weekdays are similar and during weekends the traffic volumes are similar. Based on traffic volume profiles, it is possible to predict the traffic volume so that time delays could be reduced and light levels adjusted for actual needs.

The complexity of the intelligent systems increases the risks of unreliable performance. On Ring III and VT7, since the lamp power is over dimensioned and since there have been communication problems, the real energy savings are not as great as those in the energy savings calculations.

4. Road surface luminance measurements

The purpose of road lighting is to increase the safety, rapidity and comfort of road traffic. The purpose of intelligent road lighting control is to save energy without producing negative effects on traffic safety and traffic flows. Although the light level of a road installed with a telemanagement lighting control system is varied with changes in traffic density, the changes should be such that they meet all the requirements of the appropriate higher or lower lighting class [26].

In existing intelligent road lighting control installations, traffic volume is the most commonly used control parameter, since the initial motivation to develop intelligent road lighting control systems is to decrease the light levels when traffic density is low so that energy can be saved especially at low traffic hours during the night. At the same time, energy savings should be achieved without producing negative effects on traffic safety. Therefore, other control parameters should also be considered in order to maintain lighting quality.

Road surface luminance is used as one of control parameters in the two Finnish installations, although it is not used in practice due to technical problems. In the Finnish installations, luminance meters are mounted at a height of 4 to 6 m and attached to a light pole, or a separate pole. There are fundamental problems in luminance monitoring that should be solved.

Monitoring road surface luminance is very difficult to realize in practice, as many factors may affect real-time luminance measurements, e.g. different weather conditions, disturbances of road profile and vehicles on the road. Ideally a luminance meter should be mounted at a height of 1.5 m and in the middle of a lane to be consistent with the driver’s view of luminances. In practice, it is not realistic to place the luminance meter at this height because it will get dirty very quickly, be exposed to vandalism, and heavy snow may block the view of the luminance meter. It is therefore crucial to find an optimal position for the luminance meter so that luminance measurements are reliable and the maintenance of the luminance meter is easy and economic. So far, there are no guidelines or instructions that specify where and what kind of luminance meters should be used to monitor the road surface luminance in an intelligent road lighting control system [V].

4.1 Spot luminance meters and CCD-based imaging luminance meters

Due to the novelty of the intelligent road lighting control system installations, there are no luminance meters designed particularly for luminance monitoring yet. In Ring III and VT7 installations, spot luminance meters designed for tunnel lighting control are employed for road surface luminance monitoring. These luminance meters measure the average luminance within a cone with a measuring angle of 20^o, and have an output of 4-20 mA DC for a luminance range 0-32 cd/m^2. The luminance range can be changed according to real needs. However, the observed area can not be selected freely. Once the installation height of the luminance meter is set, the maximum measuring area on the road surface is determined and the measuring area is an ellipse. The luminance meter averages the luminance values from the ellipsoid area so it does not respond to CEN road lighting measurement standard. With a CCD-based photometer, the measuring area can be freely selected from the captured images and luminance distribution can be analyzed with the aid of image processing software. These are the most important advantages of an imaging photometer over a spot luminance meter when considering road surface luminance monitoring. At the moment, imaging luminance photometers are mainly used in laboratories and companies for research and testing purpose. Due to the ease of use and the many possibilities for analyzing luminance distribution, imaging luminance photometers may provide an alternative solution for collecting information on the lighting performance of intelligent road lighting control systems [V].

4.2 Orientation of a luminance meter

Measurements were taken in order to find the optimal orientation of a luminance meter for road surface luminance monitoring. The measurements were taken on a four-lane road, VT1 between Kolmperä and Lohjanharju, which is one of the busiest highways in southern Finland. The lighting installation is provided by HPS lamps with 53 m luminaire spacing. A central reservation separates the two driving directions. The width of each carriageway (two lanes) is 8 m.

A luminance meter can be oriented transversely or longitudinally in relation to the road. Supposing a spot meter with a 20^0 viewing angle is mounted at a height of 4 m, 5.4 m from the road edge and oriented transversely, the maximum measuring area on the road is an ellipse with semimajor axis a=4 m and semiminor axis b=1.7 m, as shown in Fig. 13. If the spot meter is oriented longitudinally, placed in the middle of the road by attaching it on a bridge above the road, and installed at a height of 4 m and 9 m from the observed area, the maximum measuring area on the road surface is much larger, an ellipse with semimajor axis a=24m and semiminor axis b=4m. The maximum observed area on the road increases with mounting height and viewing angle. If the measuring area is small, this may cause inaccurate monitored luminance values when there are road markings, snow, or faulty lamps in the measuring area. For a large measuring area, these errors are relatively small because the luminance is averaged over the whole area. With an imaging photometer, the measuring area can be selected from captured images so it is still possible to get the average luminance from a large area even though the meter is oriented transversely to the road. But when a luminance meter is placed transversely, it does not correspond to luminances seen by the driver. This is emphasized with a wet road surface due to the specular reflections from the road surface. Therefore, it is recommended that luminance meters are oriented longitudinally to the road, no matter if they are spot luminance meters or imaging photometers.

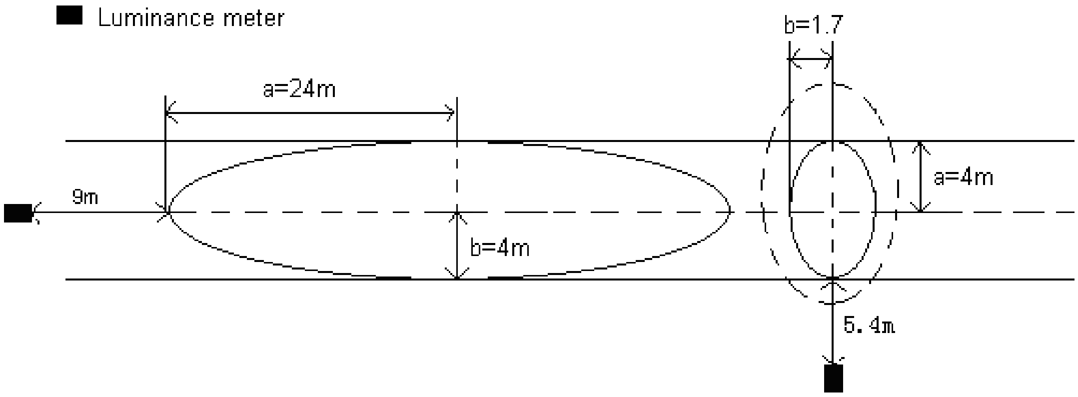


Figure 13 - Measuring area of a spot luminance meter with 20^0 viewing angle mounted at a height of 4m on road VT1.

In luminance monitoring, the effects of car head and rear lights should be considered if a luminance meter is placed longitudinally. Road surface luminance measurements were taken on VT1 in both driving directions to evaluate the effects of car headlights and rear lights on road surface luminances. The measurements were made using an imaging luminance meter LMK Mobile Advanced and analyzed by computer program LMK 2000. The luminance meter was placed in the middle of each carriageway on a bridge over the road, at Position 1 and Position 2, as shown in Fig. 14. The bridge is 6 m high and 32m from the observed areas, which are between luminaire 1 and luminaire 2. The measurements were taken at night in November, 2006 when the road surface was dry, and the measurements were completed in one hour. The road surface luminance for each driving direction was measured when there was either one car or no cars so that the effects of car headlights and rear lights could be investigated. The measurement results are shown in Fig. 15 [VI].

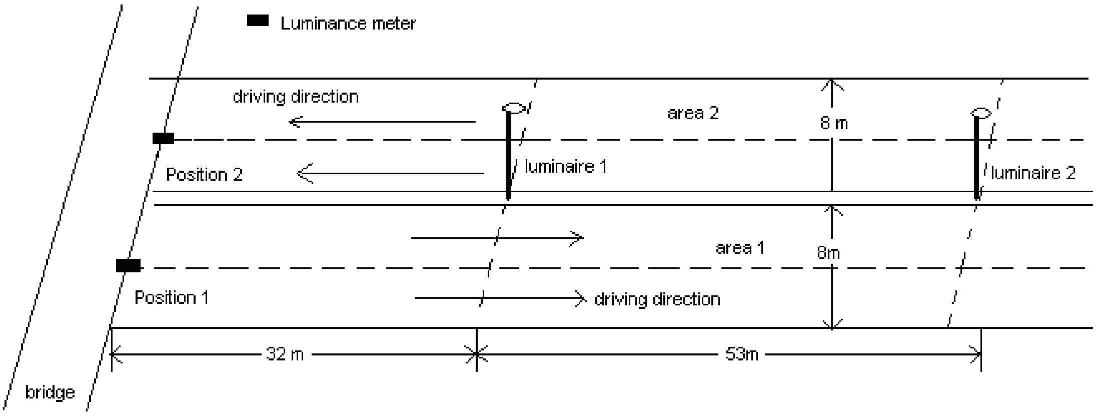


Figure 14 - Illustration of measuring positions, observed areas, and driving directions on VT1.

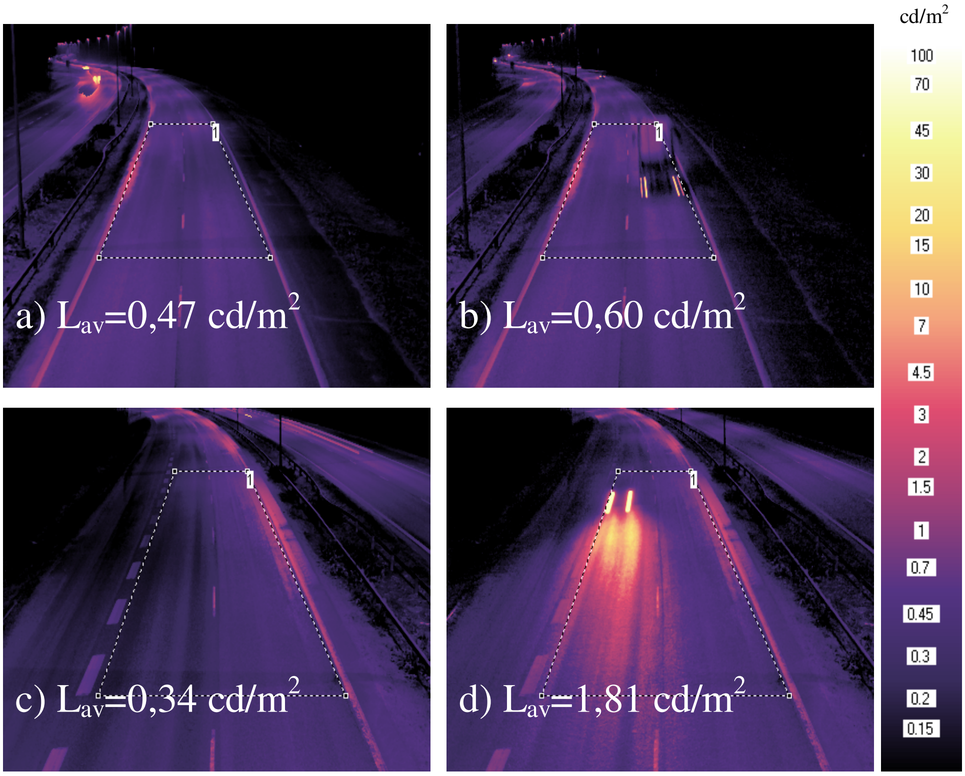


Figure 15 - Luminance measurement results on VT1 a) The luminance meter is placed at Position 1, no cars on the road b) The luminance meter is placed at Position 1, one car on the road c) The luminance meter is placed at Position 2, no cars on the road d) The luminance meter is placed at Position 2, one car on the road. L_{av} is the average luminance of the defined road surface area.

In luminance monitoring in practice, the luminance is the average value over time, so the effects of car rear/head lights are smaller than those indicated by the measurements. But the effects of car headlights are still significant for road surface luminance monitoring and may cause a malfunction of the road lighting control systems. Therefore, a luminance meter for road surface luminance monitoring should be oriented to the driving direction of the road. In practice, it is not possible to attach a luminance meter to a bridge or place it in the middle of the road in all cases. The suggested solution is to attach a luminance meter to a light pole, or a separate pole, and point it to the road surface longitudinally and to the driving direction. The measurements and discussions above are based on highways with central reservation. In case of road with two-way traffic and without central reservation, similarly as that in highways, a luminance meter should be oriented to the driving direction. And the measurement area should be on the single-direction carriageways so that the effects of car headlights in the opposite direction are minimized.

4.3 The effects of measuring height and distance under varying weather conditions

A series of measurements were taken to investigate the effects of measuring height and distance and different weather conditions on road luminance monitoring when a luminance meter is oriented longitudinally to the road and to the driving direction. The measurements were made using an LMK Mobile Advanced imaging luminance photometer and the LMK 2000 computer program [V].

The measurements were made for a local street with two lanes in Espoo, Finland. The installation is provided by HPS lamps with 32 m luminaire spacing. Fig. 16 illustrates the installation and the measuring positions. The measuring area is between two adjacent luminaires, Luminaire 1 and Luminaire 2. A car with a lifting platform was used to attain measuring heights up to 5 m. The measurements were made during three nights in February and March 2007 between 10:00 pm and 11:30 pm. The weather conditions and different positions of the luminance meter are given in Table 6.

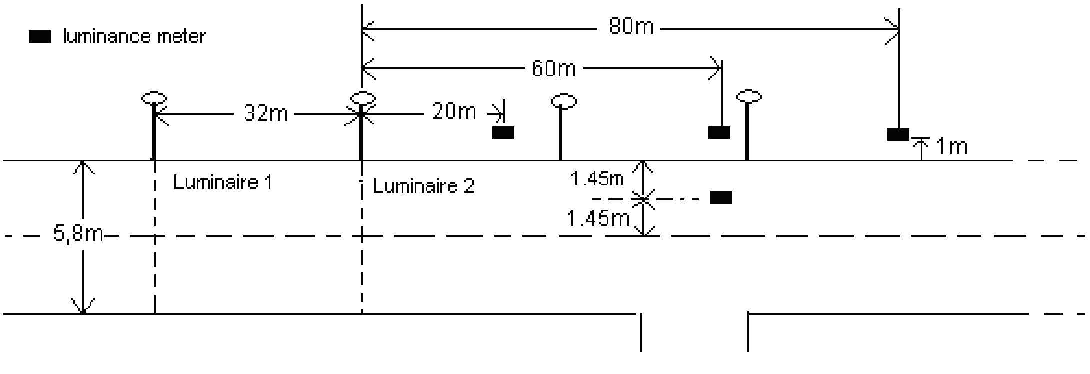


Figure 16 - Illustration of installation and measuring positions.

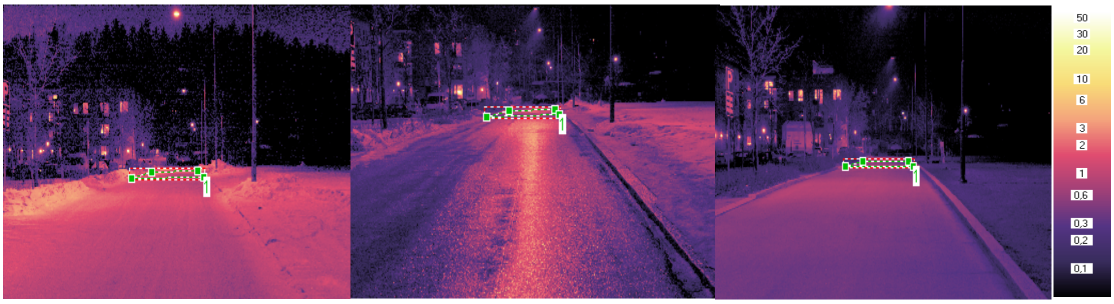
Table 6 - Weather conditions and different placements of the luminance meter in the measurements.

Date	12.02.2007	07.03.2007	27.03.2007
Time	10:00~11:30 pm	10:00~11:30 pm	10:00~11:30 pm
Road surface	Snowy	wet	dry
Road Temperature	-9 °C	1.7 °C	3.5 °C
Weather	Clear	Rain	Clear
Measuring distance	20 m, 60m, 80m	20 m, 60m	20 m, 60m
Measuring height	1.5 m, 3m, 4m, 5m	1.5 m, 3m, 4m, 5m	1.5 m, 3m, 4m, 5m

4.3.1 Measurements from the driver's position

The measurements were made from the driver's position, e.g. the observer position was at a height of 1.5m, 60m from the measuring area, and in the middle of the lane [21]. Three weather conditions (dry, snowy and wet) were investigated.

The luminance measurement results under varying weather conditions at the standard driver's position are shown in Fig. 17 and Table 7. When the road surface was covered with snow, the luminance distribution was quite uniform and road surface luminance was increased by a factor of 2.5 compared to dry conditions. In an intelligent road lighting control system, the lamp output can be decreased when road surface or the adjacent areas are covered with snow, so that a constant light level on the road surface is maintained. With a wet road surface, the average luminance of the observed area increased by a factor of 1.36 compared to a dry road surface. However, the overall uniformity under wet conditions was quite poor compared to dry and snowy conditions. Thus, in intelligent road lighting, control information of the road surface conditions is also needed, in order not to further decrease visibility by light level adjustment.



a) b) c)

Figure 17 - Road surface luminances measured from 60m distance, a height of 1.5m, in the centre of one lane under different road surface conditions, a) snowy b) wet c) dry. The observed area is the road surface area between two adjacent luminaires.

Table 7 - Road surface luminance values measured from the driver's position. L_{av} is the average luminance of the defined area. L_{av} (dry) is the average luminance under dry conditions. U_o is the overall uniformity defined as the ratio of the minimum luminance to the average luminance.

Road surface conditions	L_{av} (cd/m^2)	L_{av}: L_{av}(dry)	Overall uniformity $U_o=L_{min}/L_{av}$
Dry	0.56	100%	0.49
Snowy	1.40	250%	0.51
Wet	0.76	136%	0.33

4.3.2 Measurements from the road side

The measurements were made from the side of the luminaires, 1 m from the road edge. This simulated a luminance meter being attached to a light pole, and at different measuring heights and distances and under varying weather conditions.

When the road surface was covered with snow, the measurements were made from distances of 20m, 60m and 80m. It was possible to calculate the average luminance values of the observed road area measured at distances of 20m and 60m, while it was not possible to get any average luminance values at 80m because the measuring area was too small to be detected by the photometer and the luminaire and traffic sign blocked the observed area. Therefore, when the road surface was wet and dry, the measurements were made at two measuring distances, 20 m and 60 m. The measuring results with snowy road surface are shown in Table 8. The differences in luminances between different placements of the luminance meter are small and the measured values are very close to the average luminance measured from the driver's position. The measuring height and measuring distance do not show significant effects on the measured luminances when the road surface is covered with snow.

Table 8 - Road surface luminance values in snowy conditions. L_{stan} is the average luminance measured from the driver's position in snowy conditions.

Measuring distance	Measuring height							
	1.5 m		3 m		4 m		5 m	
	L_{av} (cd/m^2)	L_{av}: L_{stan}	L_{av} (cd/m^2)	L_{av}: L_{stan}	L_{av} (cd/m^2)	L_{av}: L_{stan}	L_{av} (cd/m^2)	L_{av}:L_{stan}
20 m	1.42	101%	1.37	98%	1.38	99%	1.44	103%
60 m	1.43	102%	1.40	100%	1.35	96%	1.42	101%

The luminance measurement results for dry road surfaces are shown in Table 9. The average luminance values are close to each other at both measuring distances, 20 m and 60 m, and at all measuring heights, 1.5m, 3m, 4m and 5m. The luminance differences between different positions of the luminance meter are in the range of -2% ~9% of the average luminance measured from the driver's position. The measuring height or measuring distance do not significantly affect the measured luminances when the road surface is dry.

Table 9 Road surface luminance values in dry conditions; L_{stan} is the average luminance measured from the driver's position in dry conditions.

Measuring distance	Measuring height							
	1.5 m		3 m		4 m		5 m	
	L_{av} (cd/m^2)	L_{av}: L_{stan}	L_{av} (cd/m^2)	L_{av}: L_{stan}	L_{av} (cd/m^2)	L_{av}: L_{stan}	L_{av} (cd/m^2)	L_{av}: L_{stan}
20 m	0.56	100%	0.56	100%	0.55	98%	0.55	98%
60 m	0.57	102%	0.61	109%	0.58	104%	0.56	100%

The luminance measurement results for a wet road surface are shown in Table 10. In these conditions, the measuring height and distance have significant effects on the measured luminances. The luminance differences between different measuring heights and distances are in the range of -53%~-3% compared to the average luminance measured from the driver's position. In areas with specular reflections towards the observation point, the luminances of the road surface increase substantially and form very bright areas. On the other hand, there are also darker areas that increase in size due to wetness. The road surface luminance measurements indicate remarkable changes caused by wetness to road surface luminances. Compared to dry road surfaces, the luminances in wet conditions can be either decreased or increased, and thus no general rules can be given for using road surface luminance as an input parameter for a road lighting control system in wet conditions.

Table 10 - Road surface luminance values in wet conditions; L_{stan} is the average luminance measured from the driver's position in wet conditions.

Measuring distance	Measuring height							
	1.5 m		3 m		4 m		5 m	
	L_{av} (cd/m^2)	L_{av}: L_{stan}	L_{av} (cd/m^2)	L_{av}: L_{stan}	L_{av} (cd/m^2)	L_{av}: L_{stan}	L_{av} (cd/m^2)	L_{av}: L_{stan}
20 m	0.59	78%	0.45	59%	0.36	47%	0.36	47%
60 m	0.67	88%	0.74	97%	0.72	95%	0.58	76%

4.4. Discussion

The measurement results under varying weather conditions are summarized in Table 11. When the road surface was covered with snow, the luminance values were substantially higher than those in dry and wet conditions. For an intelligent road lighting control system, this indicates the possibility of decreasing the light levels so that energy saving can be achieved.

For snowy road surfaces, the standard deviation of the average luminances is 0.03 cd/m^2, and the ratio of the standard deviation to the average luminance is 0.02. In dry conditions, the corresponding ratio of the standard deviation to the average value is 0.03. So when the road surface is dry or covered with snow, different measuring distances and measuring heights do not introduce relevant variations to the measured road surface luminance values. For wet road surfaces, the ratio of the standard deviation to the average value is 0.27, which is much larger than those in dry and snowy conditions. These differences indicate that, in wet conditions, luminance measuring is affected more significantly by the measuring height and measuring distance than in dry and snowy conditions. In addition to wet, dry and snowy conditions, icy road surface is another typical road weather condition. Road surface luminance levels under icy conditions and at different measuring heights were investigated in Publication VI. It was found that when the road surface was icy, different measuring heights have a significant effect on the road surface luminance [VI].

Table 11 - Average road surface luminance values in different weather conditions; σ is standard deviation and L is the average value of luminances measured at different measuring heights and measuring distances.

Measuring height (m)	L_{av} (cd/m^2) Dry		L_{av} (cd/m^2) Wet		L_{av} (cd/m^2) Snow	
	Distance 20 m	Distance 60m	Distance 20 m	Distance 60m	Distance 20 m	Distance 60m
1,5	0,56	0,57	0,59	0,67	1,42	1,43
3	0,56	0,61	0,45	0,74	1,37	1,40
4	0,55	0,58	0,36	0,72	1,38	1,35
5	0,55	0,56	0,36	0,58	1,44	1,42
σ (cd/m^2)	0.02		0.15		0.03	
L(cd/m^2)	0.57		0.56		1.40	
σ:L	0.03		0.27		0.02	

In order to obtain a larger observed area and simulate the driver's view, a luminance meter should be placed in the middle of the road and oriented longitudinally to the road. In practice, it is not possible to place a luminance meter in the middle of the road in all cases. The suggested solution is to attach a luminance meter to a bridge, a light pole, or a separate pole as close as possible to the middle of the road, and point it to the road surface longitudinally. In addition, the effects of car headlights are significant for road surface luminance monitoring, whereas the effects of car rear lights are not. So it is recommended to orient the luminance meter to the driving direction.

For luminance monitoring, installation of the luminance meter far from the observed area is not recommended. The measuring distance should not be more than 60 m, for example. As in practice the road profile is seldom completely flat and sometimes there are curves, it is quite difficult to measure the road surface if the luminance meter is far from the observed area. It is also recommended that the meter be placed at a height of ≥ 3m in order to keep the lens clean, protect it from vandalism, and from being blocked by obstacles on the road.

5. Road lighting control strategies

Although the structures of intelligent road lighting control systems are similar, the control parameters and control strategies are variable, depending on the specific case, budget and decision makers.

Time-schedule-based step dimming is a commonly used control strategy nowadays in road lighting control systems [1]. When the pattern of variation in traffic volumes is well known or can be reasonably assumed, a simple time-schedule-based control system may be appropriate. The time schedule is based on the experiences and analysis of previous traffic densities. The lamp light output is controlled centrally and can be adjusted to two to four dimming levels according to preset time schedule. The dimming schedule is essentially based on traffic volume, and lamp switch on/off time is controlled by a photocell and/or a timer. The solution is feasible and inexpensive. Significant energy savings can be achieved. The drawback is that the system does not exactly adapt to the real-time needs of light levels [I].

The initial motivation to develop road lighting control systems is to decrease the light level when traffic density is low so that energy can be saved. Nowadays, it is common to use inductive loops and cameras to measure traffic volume for traffic management. Therefore, it is possible to get real-time information about traffic volume to be used as a control parameter in the control systems. However, the systems will be more complicated because real-time information and real-time control are required.

For a real-time lighting control system, the ability to react quickly to changes in traffic flow is essential. Traffic density per hour results in reacting too slowly to the change in traffic, so it does not really adapt to the actual needs of light levels. A 15 minute or shorter period of traffic density should be used and two to four dimming levels based on traffic volumes are recommended [27]. However, there is still a time delay caused by the data collection and transmission, and time is still needed for a smooth change of dimming levels. Since there are general trends in the traffic volumes, it is suggested that light levels be adjusted based on predicted traffic volumes so that the time delay can be reduced further. It is also suggested that any scheme based upon a traffic model should be checked and evaluated continuously throughout its lifetime to ensure that it is still suitable if the traffic density levels increase or other changes occur.

With inductive loops or traffic cameras, it is possible to get the traffic volume for each lane, each direction and for all the lanes. The traffic volume of each lane is easily affected by road works. The analysis of traffic volume patterns on VT7 indicates that separate control of luminaires in the two driving directions is not necessary as the energy savings are not significant. For ease of use, it is suggested that the traffic volume in both directions be used as the input parameter. However, the number of lanes and traffic situations vary in different cases, so it is hard to give a clear definition of traffic volume for the selection of lighting classes or dimming levels.

A major consideration in road lighting control systems is to maintain proper light levels under varying weather conditions, but it is not clear yet how the visibility conditions could be taken into account. Ideally, the control parameters should indicate the visibility conditions for driving at night under varying weather conditions and characterize the complexity of traffic situations so that the proper light levels could be provided without negative effects on traffic safety. Nowadays, weather stations are installed on roadways to collect road surface information for traffic management. It is thus possible to get road surface information from local weather stations or the traffic control centre.

The luminance levels of road surfaces are usually very dynamic and depend to large extent on weather conditions. Luminances of visual objects surrounding the road (traffic signs, guiding systems, buildings, commercial lighting etc) have their effect on the luminance distribution of the visual field also. In wet conditions, the luminance distributions of road surfaces change significantly compared to dry conditions. In areas with specular reflections towards the observation point, the luminances of the road surface increase substantially and form very bright areas. On the other hand, there are also darker areas that increase in size due to wetness. Based on real-time luminance measurements, there is perhaps the possibility of benefitting from high luminance levels under snowy weather conditions [VII].

When planning a new lighting installation, the maintenance factor is taken into account due to the lamp lumen depreciation, lamp and ballast failure, dirt accumulation on lamps and luminaires, luminaire surface deterioration, and damaged light poles. Due to the maintenance factor, the light output of luminaires may be excessive when the lamps are new, but lower than required as lamps age. Depending on the lamp type and whether the installation is new or an existing installation, immediately after relamping luminaires may produce up to 20 % of light excess [25]. It is possible to eliminate this effect by dimming based on the actual lamp output needed to correct for this gradual reduction of luminous flux during the lamp life [25]. If the budget allows, a luminous flux sensor can be installed per luminaire to detect the depreciation of luminous flux. Road surface luminance monitoring is a possible solution as well.

Currently, the road lighting calculations and measurements in Europe follow the European standard EN 13201-3, which is based on road surface luminance, road surface luminance uniformities and restriction of glare [21]. The method is called the luminance design criteria. The Illuminating Engineering Society of North America (IESNA) have proposed their own luminance design criteria in the American National Standard Practise for Roadway Lighting RP-8-2000 (Reaffirmed 2005) [2]. The above-mentioned standards differ from each other, but the fundamentals of both standards are the same.

In the European standards, the selection of lighting classes for motorized traffic are based on influential parameters such as speed, traffic volume, intersection density, parked vehicles, traffic control, visual guidance and so on [28].

Traffic flow of vehicles per day (Average Daily Traffic, abbreviated to ADT) is used in describing the traffic volume in the CEN standards. For motorways (with separation of carriageways and without intersections), for ADT <15000, 15 000~25 000, >25 000, the lighting classes change from ME5 to ME2 or from ME4a to ME1 depending on the road geometry and ambient luminance as shown in Table 12, which means that the requirements for average road surface luminance will vary from 0.5~1.5 cd/m^2 or from 0.75~2.0 cd/m^2 [28]. Similarly, requirements of longitudinal luminance uniformity will vary from 0.7 to 0.4/0.5. In CIE 115-1995, it is suggested that, when the light level of a road is varied to accord with changes in traffic density during the night to conserve energy, the changes should be such that they meet all the requirements of the appropriate higher or lower lighting class (that is, if the average luminance of the road surface is reduced to that of a lower class, the uniformity and glare criteria of that class should be fulfilled) [26].

Table 12 Recommended range of lighting classes for different road situations (dry conditions) [28]

Separations of carriageways	Interchange	Intersections	Traffic flow vehicles per day		
	Spacing distance between bridges km	Density Intersections/ km	<15000	15000 to 25000	>25000
Yes	> 3		ME3a--ME5	ME2-ME4a	ME2-ME4a
	≤ 3		ME2-ME4a	ME2-ME4a	ME1-ME3a
		< 3	ME3a-ME5	ME3a-ME5	ME2-ME4a
		≥ 3	ME3a-ME4a	ME2-ME4a	ME1-ME3a
No	> 3		ME2-ME4a	ME1-ME3a	ME1-ME3a
	≤ 3		ME1-ME3a	ME1-ME3a	ME1-ME2
		< 3	ME3a-ME4a	ME2-ME4a	ME1-ME3a
		≥ 3	ME2-ME4a	ME1-ME3a	ME1-ME2
Note: The choice of lighting classes for each ADT is decided by ambient luminance, complexity of visual field, and difficulty of navigational task.					

Based on CEN standards, it is possible to define the control parameters, road surface luminance and traffic density, for real-time lighting control. For example, there can be a maximum of four levels of road surface luminance for motorways, which are 0.5 cd/m^2, 0.75 cd/m^2, 1.0 cd/m^2 for motorways classified as ME3, 0.5 cd/m^2, 0.75 cd/m^2, 1.0 cd/m^2, 1.5 cd/m^2 for ME2 or 0.75 cd/m^2, 1.0 cd/m^2, 1.5 cd/m^2, 2.0 cd/m^2 for ME1.

However, the relationship between traffic volume at a certain time period and ADT varies in different cases. The number of lanes and the road situations are different from each other. Until now, there are no recommendations or guidelines that define the detailed high, medium and low traffic density during a particular period for the purpose of road lighting control.

In ANSI/IESNA RP-8-00 2005, American National Standard Practice for Roadway Lighting, there are two design criteria: illuminance method and luminance method [2]. For expressways, major roads, collector roads and local roads, there is potential for decreasing light levels according to pedestrian conflict level. When the pedestrian conflict level is low, the illuminance/luminance level can be as low as 50% of that at high conflict level. For motorways without intersections and pedestrians, the main conflicts that may potentially endanger the road users are vehicles on the road. When the traffic density is higher, the conflict level is also higher. Therefore, it is possible to decide the dimming levels based on traffic density and conflict level for motorways as well.

At the moment time-schedule-based control systems with two to four dimming levels are the most economic and practical solution. Intelligent road lighting control systems with real-time control based on traffic density is certainly more advanced since the light levels are adjusted according to real needs. However, the complexity of the intelligent control systems results in higher risks of unreliable performance and higher construction costs.

6. Conclusions

The work started with a brief overview of the main issues concerning road lighting control systems, e.g. the visual conditions in night time driving, the light sources in road lighting, and the basic structure of telemanagement lighting control systems.

The work focused on the performance of intelligent road lighting control systems by using the examples of two installations in Finland, Ring III and VT7.

By analyzing the collected data from the control centre, it was possible to calculate the energy savings for both of the systems in the ideal case when the communication systems work properly throughout the whole year. In the ideal case for Ring III, the average power is between 50% and 60% each month, and the energy saving is around 41% compared to traditional lighting systems installed with the same luminaires. On VT7, the lamps in two driving directions are controlled separately. By analyzing the pattern of traffic volume, lamp burning hours and lamp power for a whole year, the additional energy savings from the separate control were calculated. The calculation results indicate that benefits from the separate control are not obvious.

In the two examples of intelligent lighting control systems in Finland, there have been problems in the definition of control parameters and reliability of the communication systems.

In Ring III and VT7 installations, the dimming range is set from 40% to 100% of rated power. When the lamps are dimmed to 40% of rated power, the light output is only 25% of initial luminous flux. Meanwhile, the luminous efficacy decreases greatly with dimming, e.g. when the HPS lamps are burning at 40% of rated power, the luminous efficacy is only 62.5% of the luminous efficacy when the lamps are burning at full power. Based on the dimming characteristics of HPS lamps and suggestions of manufactures, it is recommended to dim the maximum of HPS lamps to 50% of rated power. On Ring III, lamp power is adjusted with 5% steps with the traffic volume, which may result in changing lamp power continuously, whereas, on VT7, there are only four dimming levels, so the lamps can operate stably at a particular power level for a relatively long period. So continuous dimming as applied to Ring III is not suggested.

It has been expected that both energy costs and maintenance costs should decrease in intelligent road lighting control systems by reduced lamp power and instant lamp fault reporting. However, the real energy savings are not as much as the energy savings calculations, due to communication problems and over-dimensioning of lamp power on both Ring III and VT7. There is not enough information to calculate maintenance costs in the existing installations of Ring III and VT7 so far.

A payback period calculation was given for VT7 to show the cost effectiveness of the intelligent lighting control system. The initial investment costs of the intelligent road lighting control system are 16.1% higher than the traditional road lighting system. The costs of cabinets, the control system, and luminaires in the intelligent lighting system are much higher than those in the traditional system. However, those items do not represent a major part of the total costs. The costs of foundations, columns and earth work represent the most important part of the total construction costs.

The work in road surface luminance measurements should continue in order to optimize the performance of intelligent road lighting control systems since there are several practical problems in luminance monitoring at the moment.

Monitoring road surface luminance is very difficult to realize in practice as many factors may affect real-time luminance measurements, e.g. different weather conditions, disturbances of road profile and vehicles on the road. Ideally a luminance meter should be mounted at a height of 1.5 m, and be fixated to the center of the lanes to be consistent with the driver's view of luminances. In practice, it is not realistic to place the luminance meter at this height because the luminance meter will get dirty very quickly, be exposed to vandalism, and heavy snow may block the view of the luminance meter. It is recommended that the luminance meters be placed at a height of ≥ 3m in order to keep the lens clean, protect it from vandalism and from being blocked by obstacles on the road.

In order to obtain a larger observed area and simulate the driver's view, a luminance meter should be oriented longitudinally to the road, and fixated to the center of the lanes. In practice, it is recommended that a luminance meter be attached to a bridge, a light pole, or a separate pole as close as possible to the middle of the road, and point it to the road surface longitudinally and to the driving direction.

A series of road lighting measurements were taken under different weather conditions, and at different measuring heights and measuring distances. It was found that, when the road surface is covered with snow, the average luminance is substantially higher than that with a dry or wet road surface. When the road surface is dry or covered with snow, the average luminances are not affected by measuring distance and measuring height. When the road surface is wet, the average luminance values change significantly with measuring height and measuring distance of the luminance meter. The luminance values of a wet road surface may be increased or decreased compared to dry conditions, depending on the placement of the luminance meter and the wetness of the road surface. It was also found that when road surface is icy, different measuring heights have a significant effect on the road surface luminance. Careful considerations should then be taken into account in utilizing road luminance as a control parameter. Additionally, it is not recommended to install the luminance meter far from the observed area, e.g. measuring distance should not be more than 60 m.

The work continued to investigate the main control parameters and strategies that are used at the moment and tried to find the basis of the dynamic changing of light levels.

In the European standards EN 13201-1, the selection of lighting classes for motorized traffic is based on the influential parameters such as speed, traffic volume, intersection density, parked vehicles, traffic control, visual guidance and so on [28]. Based on these standards, it is possible to define a maximum of four dimming levels based on traffic volumes, depending on the different cases.

In ANSI/IESNA RP-8-00 2005, American National Standard Practice for Roadway Lighting, there are two design criteria: illuminance method and luminance method [2]. For expressways, major roads, collector roads and local roads, there is potential for decreasing light levels according to pedestrian conflict level. When the pedestrian conflict level is low, the illuminance/luminance level can be as low as 50% of that at high conflict level.

So far, although intelligent road lighting systems with real-time control may provide proper light levels based on real-time information, the benefits are compromised by the complexity of the systems, unreliable performance and higher investment. The optimal solution of road lighting control systems should be economic, simple and reliable, but may not be intelligent.

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