ADAPTIVE SYSTEMS IN ROAD LIGHTING INSTALLATIONS

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Abstract

The new revised European standards for road lighting will be published in July 2015 highlighting the importance of energy performance aspects in road installations. The adaptive lighting approach can increase energy saving and reduce the environmental impact if compared to traditional solutions with the same type of luminaires and installation layout.

For these reasons the next revision of the Italian standard on the selection of lighting classes will consider adaptive installation suggesting peculiar requirements and control strategies as supplement to the European standard requirements.

The paper describes the development of a luminance and traffic detector for adaptive system and the results of measurements carried out in more than one year on two experimental road lighting installations representative of an high volume traffic road (starting lighting class M2) and of a medium volume traffic road (starting lighting class M3).

Keywords: e.g. Photometry, Road Lighting, Energy Saving

1 Introduction

The adaptive lighting concept is defined in (CEN, 2014) as "*temporal controlled changes in luminance or illuminance in relation to traffic volume (e.g. veh/5 min), time, weather or other parameters*".

For example adaptive road lighting installations are able to maintain constant, at the requested value, the road surface luminance or illuminance despite the installation ageing, considering:

- a wide variation range of key parameters (luminous intensity depreciation of luminaire, variability of the road surface reflection properties, instability of the column voltage, etc.);
- the change of the installation lighting class according to design constraints (for example traffic volume);
- actual conditions instead of hypothetical ones linked for example to the weather conditions or emergency situations.

Conceptually we can classify an adaptive system, in ascending order of performances, as:

- **Open loop system**: the lighting class change is controlled considering a statistical estimation of the traffic volume. For example, in the Italian standard (UNI, 2012) the lighting class can be decrease by one level (i.e. from M2 to M3) if the estimated traffic volume is less then 50 % of the maximum capacity of the road and by two levels (i.e. from M2 to M4) if the estimated traffic volume is less then 25 % of the maximum capacity. The lighting class change starts at a given hour of the night according to decision the designer describes in a risk evaluation report. Generally in these systems the luminance or illuminance average value is not stable during the installation life, therefore the installation shall be over dimensioned to consider lamps and luminaires ageing and statistical variability of key parameters (tolerances in the luminaire photometric characteristics, weakness in road surface characterization, etc.). The new revision of the European standard gives guidelines (tolerance analysis) to mathematically evaluate a reasonable figure of the over dimensioning needs (CEN, 2015a).
- **Close loop system**: the lighting class change is controlled using real time measurements of one or more influence parameters like volume and typologies of traffic or weather conditions. A close loop system gives the correct lighting level required by standards for

the measured traffic volume and/or weather conditions. If compared to the open loop solution, generally this control method gives a remarkable long terms reduction in the road lighting installation energy consumption, quantified by the annual energy consumption indicator (AECI) defined in (CIE, 2015b). As a matter of fact, the statistical estimation adopted in open loop system need a safety margin and often the designer has difficulties to correctly determine local or seasonal variability of the traffic volumes. Sometime the short term comparison of the energy consumption between open and closed loop installation could be negative (i.e. more energy consumed by the closed loop installation) because of unpredicted situations, but this increment of cost for a limited period of time is largely compensated by the assurance of traffic safety conditions also during otherwise critical situations.

According to the (CEN, 2014) definition a constant light output (CLO) system (CEN, 2015b) is not strictly an adaptive system, but CLO is a functionality an adaptive system could have to improve its energy saving performances.

The CLO functionality aims to compensate for the light loss caused by ageing of the light sources. The stabilization of the luminous flux emitted by the luminaire is obtained changing the value of a control quantity (i.e. the lamp voltage for sodium high pressure lamps or the device current for LED sources) and by the knowledge of the characteristic curve *control quantity – luminous flux*. We can distinguish between two different approaches:

- **Passive**: for the light source installed in the luminaire the usual (i.e. at a constant and nominal value of the controlling parameter) reduction of the luminous flux with working time (ageing function) is statistically known and it is compensated using an *a-priori* definition of the variation rule with time of the controlling quantity. The accuracy of this approach depends on the measurement uncertainty of switch-on time, on the accuracy of the knowledge of the ageing function, on the source manufacture tolerances and on the influence of other not measured parameters, like the luminaire temperature, mains supply instability, thermal stress.
- **Active**: a quantity correlated with the real luminous flux emitted (i.e. the illuminance on a lighted surface inside the luminaire, the lamp current or voltage at constant luminaire voltage) is continuously sampled and the control quantity is changed according to the characteristic curve *control quantity – luminous flux*. In a well-designed luminaire, the accuracy of this approach is greater then the accuracy of a passive system. In the case of a photometric correlated quantity, the approach accuracy mainly depends on the measurement uncertainty of the transducer for this quantity. Key parameters are the transducer stability with time and temperature, its repeatability between switch-on and off cycles and its ageing. Of course a correct transducer calibration in absolute units is too expensive and generally not technically justified or required. As a consequence, the luminaire emits a luminous flux with a value inside the standard tolerances (IEC, 2004), and it is this unknown value but within the tolerance limits (usually between the rated value and -10% of the rated value) that is maintained stable during the luminaire operating life or between maintenance actions.

In road lighting installation this approach has several weak points:

- Only the luminous flux of the light source is maintained constant, but the luminous flux and the luminous intensity distribution of the luminaire also depend on the ageing of the optical components and the influence of dust inside and outside the luminaire.
- The over-dimensioning of the road lighting installation should not be avoided but only reduced. Practically only the influence of the lamps ageing (lumen maintenance) can be deleted in the maintenance factor evaluation. The influence of the a.c. mains supply conditions can be reduced using luminous flux controllers that usually are a more simple solution.
- For motorized traffic (CIE, 2010) and European standards (CEN, 2015c) the lighting level is quantified by the maintained average road luminance value given in the M set of lighting classes. Therefore the variability and ageing of the road surface characteristic in reflection (CIE 2001) are important factors that should be considered in order to guarantee the standard requirements with the minimum energy consumption.

To overcome these limitations REVERBERI Enetec developed a detector (LTM) able to measure the motor traffic volume and road average luminance. The research programme REGOLO obtained the financial contribution of Regione Lombardia (Italy) and was done in collaboration with INRIM (the Italian National Metrological Institute) that characterized the metrological performances of the detector and of the road lighting installations and Provincia di Bergamo that provided the test sites (selection and management of the road lighting installation).

The LTM detector permits to realize a close loop adaptive system able to:

- Select the correct lighting class according to the traffic volume,
- Detect weather conditions,
- Maintain the road luminance equal to the maintained average value required by standard for the given lighting class,
- Detect anomalous situation like the presence of car queues and wet road surface.

2 European Standard requirements

The new European standard for measuring the lighting performance or road installation (CEN, 2015a) gives requirements according to the measurement aims and in its normative annex D considers measurement systems for adaptive road lighting. To avoid technically unjustified costs for luminance measurement, the standard suggests strategies to simplify the measurement system and the operating conditions without compromising the measurement aims. The measurement uncertainty of the controlling system should be evaluated considering not only the instrumental contributions but also the contributions due to installation conditions should be considered in order to be sure to guarantee the maintained value of the photometric quality parameters as required in (CEN, 2015c).

These simplifications can modify the road lighting design approach too and their consequences should be clearly understood.

Set measurement: the set measurement is defined as "*measurement carried out in an installation to determine the values of parameters used by an automatic measuring system for control purpose*" (CEN, 2015a) and it can be considered as a sort of calibration of the detector carried out in the field and in its actual operating conditions. This procedure avoids or reduces the necessity of a complete characterization of the detector in laboratory, it takes into account also the peculiar position of the detector respect to the observer position defined in the standard (CEN, 2015d) and the detector – road surface distance.

Particular parameters: if the control system does not modify the installation uniformity values, it is possible to measure directly the average road luminance but avoiding the influence of road marking. Formally this is the measurement of a particular parameter as defined in (CEN, 2015d). The measurement can consider the entire grid zone, a significant part of it or more than one grid zone. This simplifies the optical system, reduces spatial resolution requirements of the sensor and its alignment procedure. Instrument constants that link the peculiar parameters measured to the standard ones shall be known. These values can be obtained from the set measurement.

Detector position: of course it is not possible to put the luminance detector in the position defined in the standard (CEN, 2015d). The correlation between the road luminances considering the detector real position and the standard observer can be obtained using the set measurement or peculiar calculations. Also statistical knowledge of the road surface photometric characteristic with different angles of observation can be used, but this approach usually increases the measurement uncertainty. Practically there are two technical possibilities in selecting the new position of the luminance detector and a compromise between the *pro* and *contra* of the two solutions should be considered.

- A luminance meters with a narrow measurement cone can be used at a greater height than the standard observer. The meters measures the luminance on a road surface at a proportionally greater distance so that the angle of view of the meter is (89 ± 0,5)° to the normal to the road surface. This solution tries to maintain the standard view condition, but works at greater distance, so the influence of the atmospheric luminance or attenuation is higher and the mechanical stability of the detector becomes critical especially in windy zones.

- The luminance meters at a greater height than the standard observer frames a zone of the road surface with an angle lower then the standard (89 ± 0,5)°. As the observation angle decreases the specular component of the reflectance of road surface decreases and the road surface becomes like a lambertian surface. In this conditions the detector measure a luminance proportional to the illuminance on the road surface instead of the luminance in standard conditions

Detector characteristics: the detector should be characterized considering the quality parameters define in (ISO/CIE, 2014). But some simplification can be adopted.

- The calibration of the luminance meter can be omitted if the set measurement concept is adopted and if this measurement guarantees the traceability of the controlled parameter. In this situation the set measurement gives a sort of calibration factor to the control system that take into account not only the characteristics of the detector but also its position and the road lighting installation conditions.
- The deviation of relative spectral responsivity from the $V(\lambda)$ function (f'_1) is less important if the set measurement concept is adopted, but during the life of the road lighting installation the spectral emission of the luminaires can change as well as the spectral reflectance of the road surface. For these reasons it is preferable to minimize the value of f'_1 or to adopt strategies to minimize its influence in the measurement uncertainty like the correction of the measured value considering the type of lamp and its correlated colour temperature.
- Luminaires or extraneous and obtrusive lights framed or not framed by the detector can influence its reading due to inter-reflection in the lens or between the lens and the protective glass in the detector box. The parameter $f_{2,u}$ becomes very important especially in urban road lighting installation. Any characterization of the detector concerning this aspect shall be done with the detector in its box and with all the screens installed.
- Other not photometric characteristic can become very important. The detector will work at very different temperature conditions (winter – summer, day – night) for long period of time. Its stability, long term ageing, repeatability, the influence of working temperature and humidity generally different form those present during the set measurement, the possible presence of condensation or moisture in its lens, the thermal stress are aspects that should be considered in evaluating the measurement uncertainty. The use of a thermally stabilized box can reduce the influence of these conditions.

Extraneous and obtrusive lights: Extraneous and obtrusive lights may not be avoided during measurements. During the set measurement the influence of extraneous and obtrusive lights may be evaluated, for example some measurements can be carried out with the road lighting installation switched off.

3 Proposal for standard requirements

A new revision of the Italian standard (UNI 2012) is in development and will consider in details the close loop adaptive systems with luminance control.

Many aspects are not considered in the European standards but some normative requirements are necessary to avoid unsafe conditions. The main points under discussion are described in the following where only the opinion of the authors is given.

- Extraneous and obtrusive lights: they could increment the road surface luminance but also the glare condition. The detector cannot evaluate the glare to which the observer is exposed because its position is completely different and it is quite impossible to determine the correlation between the measured glare and the observer glare. In the risk analysis the designer should evaluate the presence of extraneous and obtrusive lights and decides the possible set of lighting classes. The adaptive system controls the road luminance considering the real road luminance as sampled.

- Presence of rain, fog or snow: the reading of the luminance meter becomes unreliable because the instrument performances may change but also the atmospheric attenuation and diffusion change dramatically. If required by the standard, the designer shall select the lighting classes that should be used in these situations. The detector should be able to identify these anomalous situations and the correct lighting class activated using the control coefficient or factors adopted previously for the same lighting class.
- Traffic volume: it could be evaluated in a given relatively long period of time (for example 15 min) and then the lighting class modified according for the next 15 min or it could be sampled in a short period of time (for example 1 min) and a moving average evaluated considering for example 10 samples. Sudden variation of luminance shall be avoided so the decrement of luminance should be done with a long time constant while the increment requires a short time constant for safety reasons. A continuous variation of luminance proportional to the measured traffic volume could be a permitted procedure to avoid sudden variation of luminance and decrease energy consumption without a perceptible decrease of traffic safety.
- Unwanted operating conditions: when the measurement conditions give wrong results the control system shall maintain safety condition i.e. shall adopt control strategies that guarantee the required value of the average luminance for the correct lighting class. Typical situations are the stabilization period of the lamp after the evening switch-on of the installation, climatic conditions that do not represent the conditions required by design and management of the road lighting installation, the detector working conditions (temperature, humidity, condensation or moisture on light transmitting surfaces) outside its operating range.
- Detector failure: also in this situation the luminance reading is unreliable. As before the control system shall maintain safety condition of road traffic.

4 Road lighting installation design

To obtain the best performances of a close loop adaptive systems with luminance control, the designer of the road lighting installation should consider that the system will always operate near the minimum average luminance value required by the standard.

The installation over-dimensioning can been divided into two group of components:

- The components described by the maintenance factor that hypothesizes a continuous reduction of the lighting level with time (CIE, 2003).
- The components due to other parameters. In the design phase this component can be statistically evaluated using the tolerance algorithm described in (CEN, 2015a) considering for example the tolerance in manufacturing of the photometric characteristic of luminaires and light sources with reference to rated value, the influence of ambient temperature, the layout tolerance of road lighting installation and of the installation of the light source and the uncertainty of the road surface photometric characteristics.

Also in this application, the measurement uncertainty shall be minimized and a compromise between detector and control system cost and measurement accuracy should be carefully considered. As the compliance with standard requirements shall be verified considering the expanded measurement uncertainty of the measure (CEN, 2015a) the measurement uncertainty should be considered in the over-dimensioning (second group) of the installation, as clearly highlights in figure 1.

In figure 1 a traditional installation is compared to an adaptive solution considering for simplicity a single luminous class. The traditional installation works at constant power consumption. Its luminance decreases from the initial values to the final value that, for a wrong estimation of the over-dimensioning, is greater then the standard maintained value. The adaptive system works at constant luminance. Its energy consumption increases with time but it is always lower than that of the traditional system. In this case the over-dimensioning has no consequences in the management cost. It represents a cost only in the installation phase.

The measurement uncertainty of the control system represents a cost in term of additional energy consumption. For this reason this uncertainty shall be specified in the road installation project, because it influences the installation energy performances.

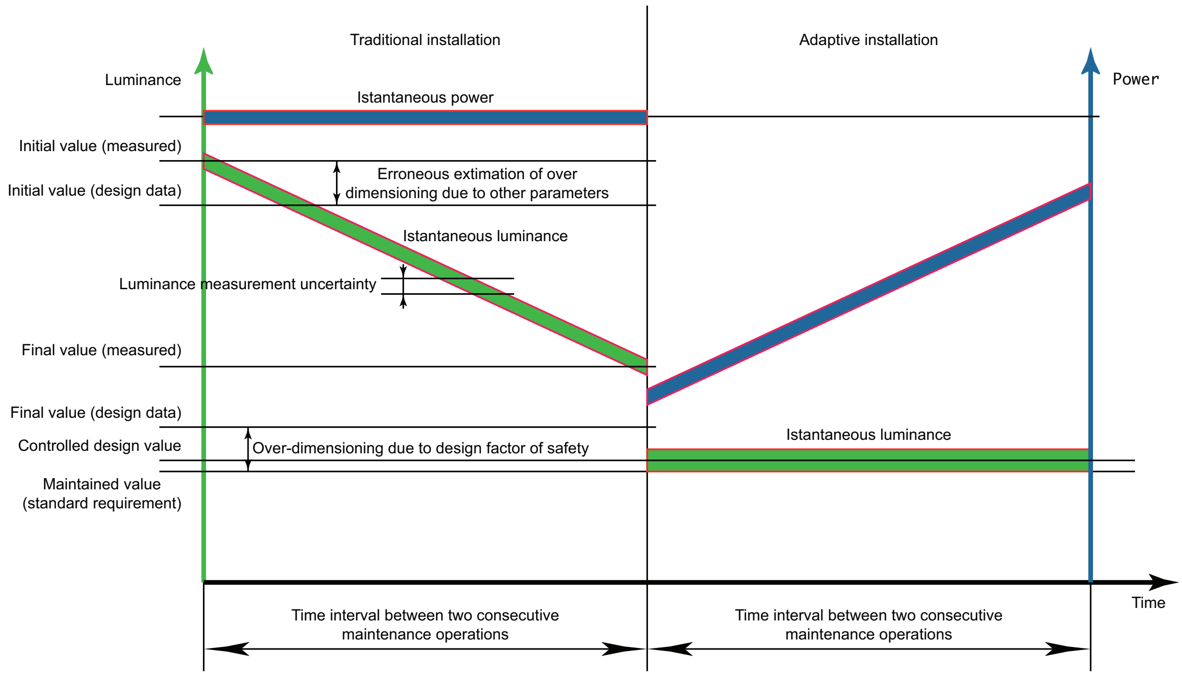

Figure 1 – Comparison between a traditional road lighting installation (left) and an adaptive solution (right). The luminance and the power consumption versus time of the two systems have been drawn.

5 The measurement of road surface luminance

The detector used in the LTM system is a colour camera (Bayer filter) with a CMOS sensor, an infrared filter and a long focal lens.

The optical system is designed to operate between 60 m to about 200 m (figure 2) and the road surface point luminance is obtained considering the weight sum of the reading of the four close pixels of the Bayer filter.

The spectral responsivity of the single colours of the Bayer filter has been measured using a modified Perkin Elmer Lambda 900 spectrometer with the lens and the protective glass in front of the detector. Then the weight coefficient for every colour has been evaluated to minimize the f'_1 value.

To increase the accuracy of luminance measurements, the luminance value obtained is multiplied by different calibration factors considering the lamp type and its correlate colour temperature. The selection of the lamp type is done automatically in the field considering the ratio between the signals of the three colour of the Bayer filter.

The corrected luminance value is then multiplied by the calibration factor obtained from the set measurements.

The measurement zone of the road is selected during the installation of the system observing the acquired imagines.

In a well-design system the main contribution to the measurement uncertainty should arise from the set measurement. Considering a measurement uncertainty of 3 % for this measurement the system is able to work with a 5 % uncertainty.

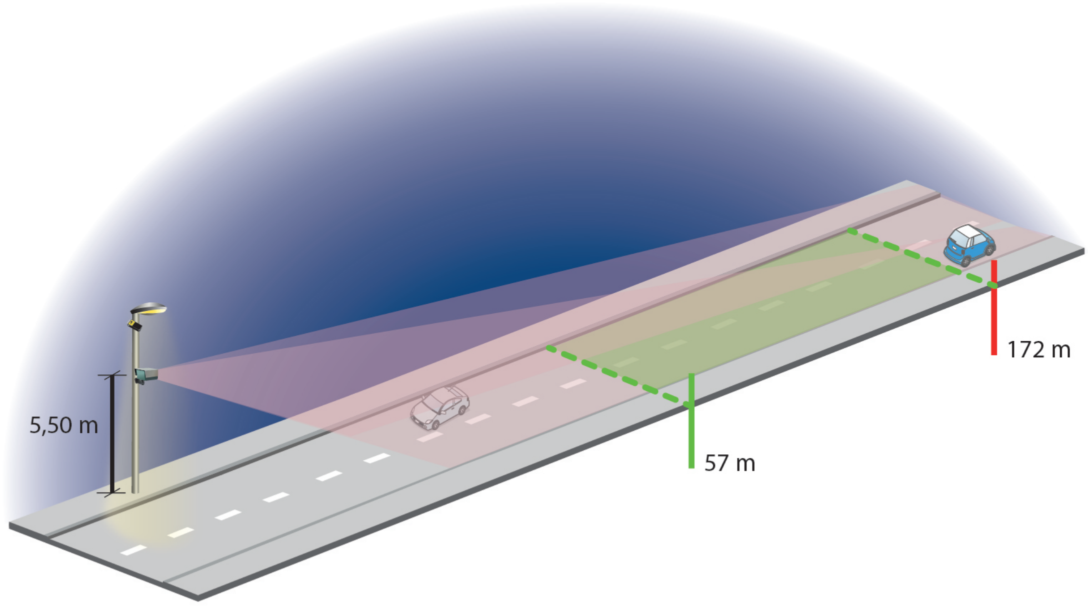

Figure 2 – Typical conditions of installation of the LTM detector

The same sensor is used to measure the traffic volumes using a proprietary algorithm to count the number of vehicle in the given time interval. If compared with traditional systems considered exacts, the count uncertainty is less then 10 %. The image analysis algorithm counts the vehicles but it is also able to detect if there are vehicle in the zone selected for the luminance measurement or if the headlamps of vehicles can influence the luminance measurement. The two acquisition processes (for luminance measurement and for vehicle detection) are carried out with different integration times of the detector to reduce the influence of saturated pixels or noise.

6 Experimental data

Two experimental road lighting installation (table 1 and figure 3) has been tested for more than one year. The installations represent two typical not urban situations.

Table 1 – Description of the two experimental installations

Installation	Mornico	Treviolo
Position (Latitude Nord)	45° 35' 23,16"	45° 39' 43,98"
Position (Longitude East)	9° 49' 0,05"	9° 36' 30,52"
Description of road	Two lane road with single side luminaire arrangement	Four line road with central reservation and central luminaire arrangement
Type of lamps	Metal Halide	High pressure sodium
Lighting classes	M3 – M4 – M5	M2 – M3 - M4

Figure 3 – The road lighting installation at Mornico (left) and at Treviolo (right)

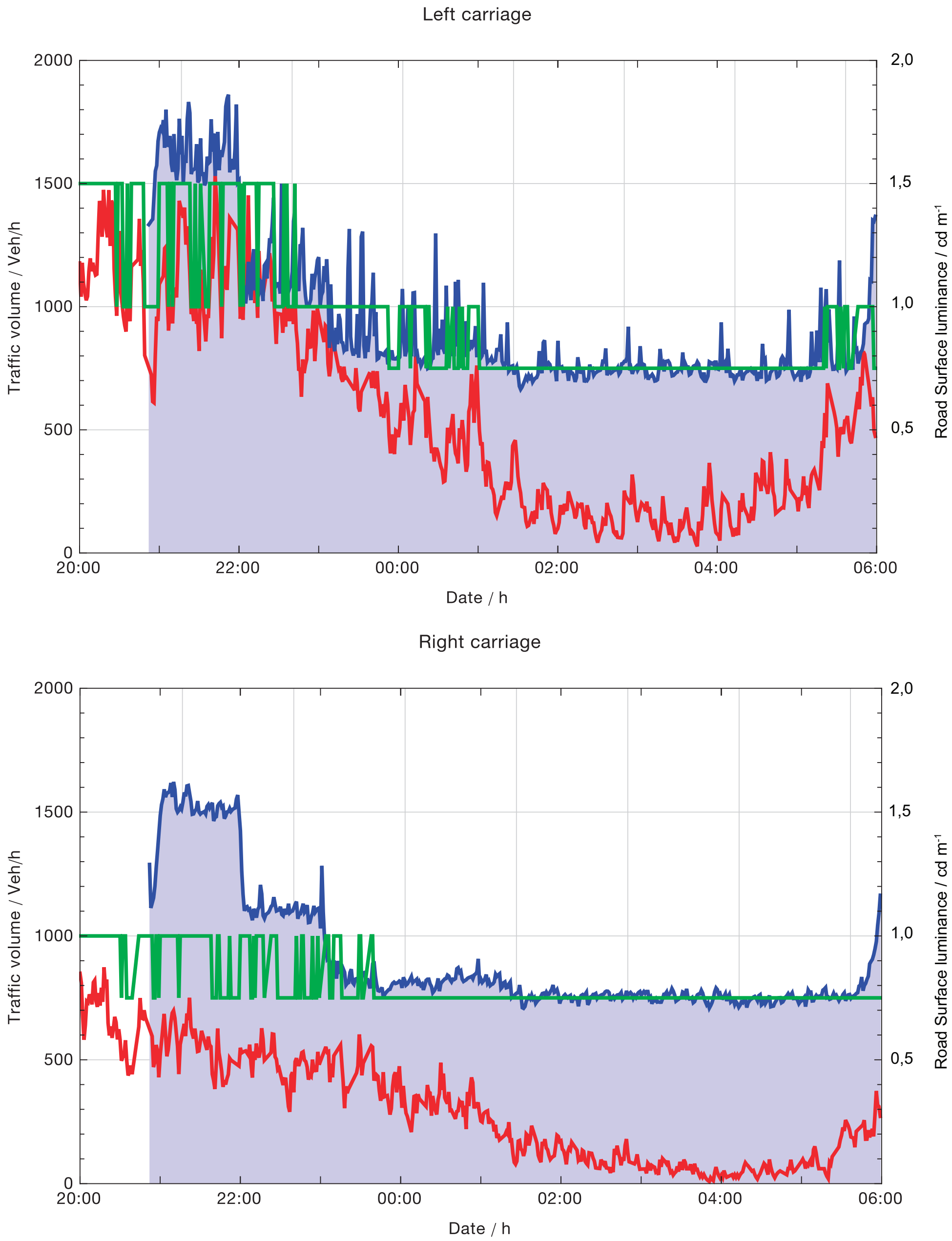

Figure 4 – Example of the traffic volume and operating condition of the Treviolo installation during the 12 August night. The red curve is the measured traffic volume, the blue curve the measured road luminance and the green curve the standard luminance required considering the measured traffic volume.

The more interesting results have been find in the Treviolo road. The differences in the traffic volumes at the same time between the two carriages (in the morning high traffic volume in the town direction and vice-versa in the evening) justifies the realization of two independent system because the energy saving can be as great as 25 % respect to a single system installation. This situation is clearly shown in figure 4 where all measurements are given without averaging process. The road luminance has been controlled to the level required by design (open loop system). The traffic volume is quite different in the two directions and there are situation when the a-priori selection of the lighting class does not guarantee safety.

7 Conclusions

The experimental results show the great potentiality of adaptive system with a continuous control of the road luminance level, but highlight the necessity to follows clear rules for the luminance control to optimise the energy saving and the traffic safety: the energy consumption reduction is also strongly correlated to these choices. Unconventional control strategies, like the continuous but filtered variation of the luminance with traffic volumes could adopted but the require a revision of the national standard.

In the two experimental installations, if compared to the condition before the installation of the LTM system, the energy consumption has been reduced for about 35 %.

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