A NEW REAL TIME INTELLIGENT MANAGEMENT MODEL FOR STREET LIGHTING

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Abstract

The International Commission on Illumination issues certain recommendations regarding the use of public lighting at night without however giving guidelines on the dimming method.
However, intelligent management of the time lighting is switched on and off lighting power levels which reflect traffic conditions are essential for providing high-quality public lighting and achieving significant energy savings.
This study sets out an intelligent lighting model which combines two real-time lamp-power dimming principles: spreading and the transfer curve. This model allows the power and time the lamps are lit to be adjusted according to the position and speed of road users. In addition, integrating the mesopic vision model reduces the maximum power of the lamps while maintaining photometric perception that is similar to that required in photopic vision conditions.
The intelligent real-time lighting management model developed in this study allows substantial energy savings to be made while providing users with an optimum visual comfort and level of safety.

Keywords: Intelligent management of public lighting ; mesopic vision model ; energy saving

1. Introduction

In a difficult economic and ecological context in which energy is an issue of great importance, public lighting represents 40 % of the electricity costs for public authorities in Belgium.
The use of LED technology and the application of a mesopic vision model combined with an intelligent lighting control system can result in significant energy savings.
Following the recommendations of the International Commission on Illumination (CIE), which allows an adaptation of the lighting classes according to parameters related to traffic, various studies have been conducted on lamp-power dimming (CIE 2010).
Although these studies show interesting results in terms of energy saving, the dimming methods that are applied do not consider any change in the flux of the lamps in real time according to traffic conditions (Europe 2008; Guo L. 2008; Halonen L., Guo L. et al. 2008; Bjelland E., Mjos T. et al. 2009; Onaygil S. and B. 2009). These control systems reduce the lamps' flux at certain set times of the night according to previously measured average traffic. These methods are useful for roads with continuous traffic throughout the night, but in other cases, such as business parks where traffic at night is significantly reduced in comparison with traffic at day, a more sophisticated control system can provide larger energy savings.
It is in this context that an intelligent management method of public lighting according to traffic conditions in real time has been developed. This management model combines the integration of the mesopic vision model with two original dimming principles: spreading of the maximum power and the power transfer curve.
Spreading allows the power level required for a normal lighting level class to be changed to a level required for a class which is adapted to the variation in traffic during the night (CIE 2010).

The power transfer curve allows the lamp power to be varied continuously according to the position and speed of the user.
This model has been developed and installed in a business park in the region of Liège (Belgium) and will soon be validated[1].
In the case of this business park, the implementation of this model, combined with LED technology and the mesopic vision model theoretically allows an energy saving of up to 77 % to be made.

2. Development of the model

The design of street lighting is based on the definition of the lighting classes which are selected on the basis of criteria related to the geometry of the road, the user and the environment (CIE 2010). When designing street lighting, the most demanding criteria must be selected to define the most demanding normal lighting class for the road.
Since these criteria vary during the night, other, so-called "adapted" classes are also applicable for reducing the power of lighting during the night (CIE 2010). During those periods for which a low-light lighting class level is specified, various methods for reducing lighting may be applied (IBN 2004).
The intelligent lighting management model developed in this study is based on the real-time variation in the conditions of traffic volume and speed.
Based on these normative considerations, this model combines two lamp-power dimming principles:

- *Spreading* sets a maximum lamp power level required for the lighting class (normal or adapted) actually active according to the traffic conditions.
- *The power transfer curve* allows the lamp power to be varied continuously, according to a sigmoidal distribution, from maximum power for the activated lighting class to minimum safety power, according to the position and speed of the user.

2.1. Spreading

Given the variability of the criteria linked to the selection of the lighting classes, there may be different adapted classes for a single road. The street lights located on this road must therefore provide power levels adapted to the class actually active according to the traffic conditions. The various levels of the spreading principle are the levels of maximum power that the lamps must provide to meet the photometric requirements of the active lighting class.
The maximum power level is determined by the type of lamp used and the photometric requirements of the different lighting classes.
Different levels of power are selected to match the luminance requirements of the different activated classes according to the variability of the parameters related to the traffic.
In addition, the use of the mesopic vision model and LED lighting technology can also reduce these power levels compared to photopic photometry. Indeed, given an equal photometric requirement and therefore an equal lighting class, an efficient lamp in the mesopic field (S/P=2,05) reduces by about 20 % the installed capacity, compared to the photopic model for an undemanding lighting class (CIE 2009).

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[1] The GEPPADI project (Sustainable and Intelligent Public Lighting Management in Business Parks), funded by the Walloon Region, is organised in partnership with companies of ARTHOS Technics and Ets. E. Ronveaux SA, SPI, the economic development agency for the province of Liège, the Électronique, Microsystèmes, Mesures et Instrumentations unit (EMMI) at the Université de Liège and the Architecture & Climat laboratory of the Université catholique de Louvain.

2.2. The power transfer curve

The Belgian standard (IBN 2004) and the International Commission on Illumination (CIE 2000) define a standard calculation field for the area of interest to the user of the road for which the photometric requirements must be checked. According to the Agence Française de l'Eclairage - French Lighting Agency (AFE), it is assumed that the driver observes a section of road located between 60 m and 160 m in front of the vehicle, his eyes being placed 1,5 m above the level of the road (Agence Française de l'Eclairage 2002).

Therefore, basing our calculations on the geometric design of the roads (Vertet and Giausserand 2006) and the tunnel lighting guide (CIE 2004), we define the area of the road of interest to the driver according to the driving task for which the stopping distance, equal to the distance of visibility plus 60 m, is a representative measurement of the area.

The principle of the power transfer curve (Figure 1) is based on this notion of distance of visibility DV (Equation 1).

$$DV = v * t_r + \frac{v^2}{2g(f+p)} \quad (1)$$

where

- v is the speed of a user ($km \cdot h^{-1}$)
- t_r is the reaction time (including the mechanical transmission time of the brakes and the physiological time of perception and reaction) which is 2 s
- g is the constant of acceleration $g=9,81\ m \cdot s^{-2}$
- f is the coefficient of longitudinal friction (value between 0 and 1) that varies according to the speed. This factor accounts for pessimistic parameters such as the state of fatigue, the wetness of the road, the tire condition.
- p is the lengthwise slope of the road profile (m/m)

The power transfer curve model was developed on the basis of the following five axioms:

- *Axiom # 1: maximum and minimum power*
  Maximum power P_{max} (in watt) of the lamps varies according to the activated lighting class (spreading principle). The minimum safety power P_{min} (in watt) is dependent on the lamp or the lamp driver.

- *Axiom # 2: the distance of interest*
  Ahead of the user, lighting is provided at full power (P_{max}) over a distance of interest for the user X_{100} (Equation 2). By definition, this distance is equal to the distance of visibility DV plus 60 m. If the distance of visibility is less than the gap e between two successive street lights, the distance of interest is then 60 m increased by the distance between the two street lights. We therefore establish the distance of illumination at full power or "distance of interest":

  $$X_{100} = 60 + max(DV, e) \quad (2)$$

  where
  - DV is the distance of visibility (m)
  - e is the gap between two successive street lights (m)

- *Axiom # 3: the position of the inflection point*
  The power transfer curve increases from P_{min} to P_{max} via an inflection point located at a distance X_{50} (in metre) (Equation 7) ahead of the user. X_{50} varies according to the offset distance d (Equation 3). This offset distance itself is proportional to the distance of visibility DV. The coefficient of proportionality k (Equation 4) is called the expansion coefficient and varies according to the speed of the user and the maximum allowed speed on the road.

$$d = X_{100} + k * DV \quad (3)$$
$$k = \beta \frac{v_{aut}}{v} \quad (4)$$

where

X_{100} is the distance of interest (m)
k is the coefficient of expansion (/)
DV is the distance of visibility (m)
β is a coefficient of proportion (/) (Table 1 and Figure 2)
v_{aut} is the maximum authorised speed on the road ($km \cdot h^{-1}$)
v is the speed of a user ($km \cdot h^{-1}$)

- *Axiom # 4: the symmetry of the power transfer curve*
  The dimming of the street lights located behind the user is relatively symmetrical compared to the power dimming curve of the street lights located ahead of the user. The coefficient of symmetry Δ varies according to the speed of the user, in favour of slow users (pedestrians, cyclists, etc.) (Table 1 and Figure 2). Since these users may turn around quickly, their visual perception must not be changed if they do turn around.

- *Axiom # 5: the steepness of the power transfer curve*
  The transfer of power of the street lights from P_{min} to P_{max} and conversely behind the user, occurs more slowly the slower the user is travelling. The coefficient of steepness of the curve ρ (Equation 5) controls this hypothesis and varies according to the ratio of the user's speed to the maximum allowed speed on the road:

$$\rho = \frac{v}{v_{aut}} \quad (5)$$

where

v_{aut} is the maximum authorised speed on the highway ($km \cdot h^{-1}$)
v is the user's speed ($km \cdot h^{-1}$)

Given the above-established axioms, the power transfer curve is expressed by a sigmoid curve, the transformation of a standard normal distribution function. This function allows a minimum value to increase to a maximum value via an increase phase which is then followed by a decrease phase.
The power transfer curve is therefore a sigmoidal transformation function which gives the power value of each street light located within a certain distance of the user. The power transfer curve regulates the dimming of each street light and is therefore, "attached" to the user and moves at his speed. Given,

$$\boldsymbol{P(x) = P_{min} + (P_{max} - P_{min}) * \left(\frac{d^n}{d^n + \rho\, x^n}\right)} \quad (6)$$

Minimum safety power — Field of power (spreading) — Transfer function (speed and position of the user in the street)

where

P_{min} is the minimum safety power (W)
P_{max} is the maximum power (W) according to the activated class (spreading)
d is the offset distance (m)
n is a tabulated variable for smoothing the transfer curve (/)
ρ is the coefficient of steepness of the transfer curve (/)
x is the position of a street light compared to the user (m)

The variable n is tabulated according to the maximum authorised speed v_{aut} ($km \cdot h^{-1}$), the maximum power of the street lights according to the activated class P_{max} (w), the minimum safety power according to the street light and/or the lamp driver selected P_{min} (w) and the speed of the user v ($km \cdot h^{-1}$)
P(x) therefore gives the value of power that a street light must provide when a moving body moves in its direction, where x is the position of the street light in relation to this moving body (Equation 6).
The street light increases its power from P_{min} to P_{max} as the moving body approaches it and reduces its P_{max} power to P_{min}, relatively symmetrically, as the moving body moves away from it. The power transfer curve is a function of the maximum power P_{max} and minimum power P_{min}, of the distance of interest X_{100}, of the position of the inflection point X_{50} and of the coefficient of symmetry Δ.

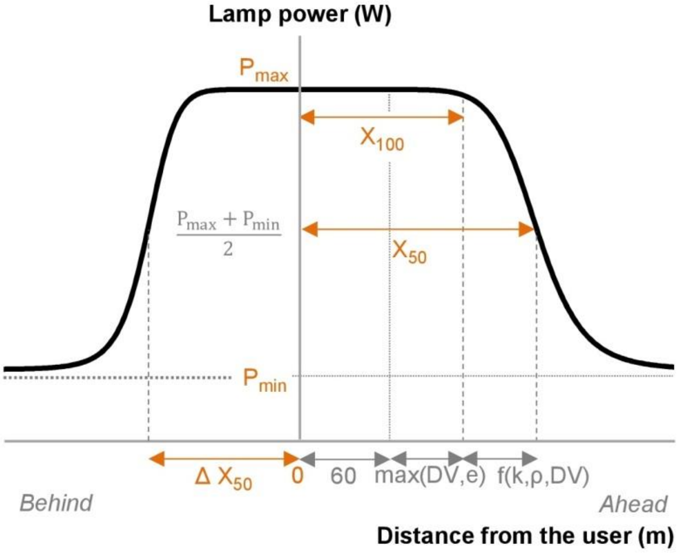

Figure 1 : Power transfer curve

On the basis of the definition of a sigmoidal function, we can determine the position of the inflection point of the increase in power of the street lights:

$$X_{50} = \left(\frac{d^n}{\rho}\right)^{1/n} - X_{100} \quad (7)$$

where

d	is the offset distance (m)
n	is a tabulated variable for smoothing the transfer curve (/)
ρ	is the coefficient of steepness of the transfer curve (/)
X_{100}	is the distance of interest (m)

The coefficients of expansion k, steepness ρ and symmetry Δ depend on the user's speed category. These speed categories are identical to those established in the process of selecting the lighting classes (IBN 2004). The values associated with these parameters are set deliberately so as to favour users in terms of visual comfort, safety and a luminous atmosphere.

- Low-speed users ($v \leq 30$ $km \cdot h^{-1}$) may turn around quickly; this means that the power transfer curve is symmetrical in relation to the position of the user : Δ=1.
- Pedestrians and cyclists must perceive a slow change in the power of the street lights i.e. the transfer curve is expanded : k and β are therefore high.

- The power transfer curve for motorised users (v > 30 $km \cdot h^{-1}$) must not be symmetrical (Δ< 1) and may undergo an increase and decrease which is steeper than that of low-speed users: ρ is small.

Table 1 : Parameters of expansion, symmetry and steepness of the power transfer curve

Speed category ($km \cdot h^{-1}$)	*Expansion (k) β*	*Symmetry Δ*	*Steepness ρ*
v ≤ 5	1,5	1	Maximum speed of the category, divided by the maximum authorised speed
5 < v ≤ 30	1,25	0,85	
30 < v ≤ 60	1	0,65	
v > 60	0,75	0,5	

- The expansion parameter k (and therefore β) enables lighting which projects further or nearer and therefore a transfer curve which more or less expanded : the higher β is, the more the transfer curve is expanded
- The parameter of symmetry Δ regulates the level of symmetry between the increase in power of the street lights in front of the user and a decrease in power of the street lights located behind the user : the more Δ tends to 1, the more the curve is symmetrical.
- The ρ steepness parameter determines the speed with which the street lights increases and decreases in power during the passage of a moving body : the greater ρ is, the steeper the transfer curve.

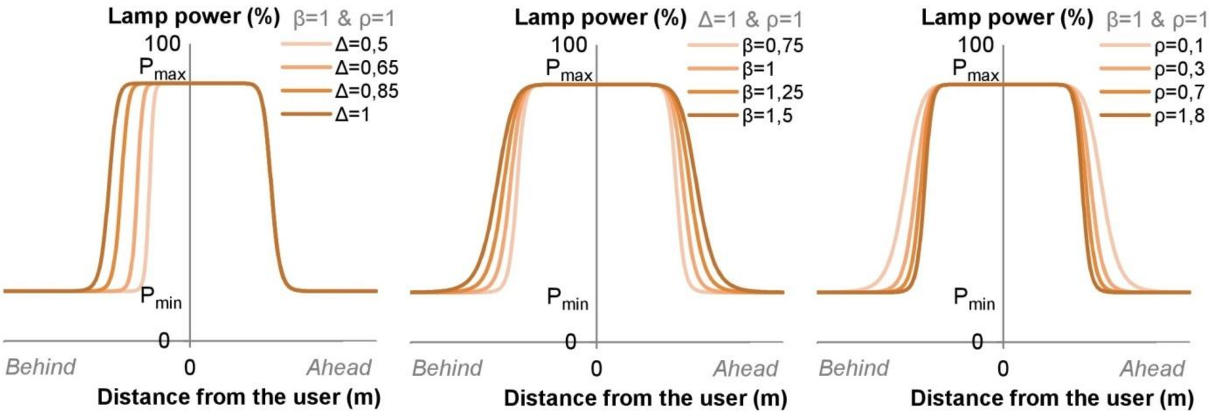

Figure 2 : Parameters of symmetry, expansion and steepness of the transfer curves

3. Simulation on a pilot site

The intelligent lighting management model (spreading and transfer curve) has been implemented on a pilot site. This pilot site is undergoing renovation: the current high pressure sodium lamps will be replaced by LED lamps and the intelligent lighting management model developed above will be implemented.
This site is composed of two roads, limited to 50 $km \cdot h^{-1}$, for which the total power consumption (before renovation) of the site is 18 644 $kWh \cdot year^{-1}$. The installed capacities in Street 1 and in Street 2 are respectively 92 W and 127 W. 22 street lights are currently lit for 4 085 hours/year in Street 1 and 20 street lights are lit for the same amount of time in Street 2. The selection of the lighting classes (normal and adapted) for each of two streets is based on an hourly reading of the average traffic (ATH). This selection shows 3 levels of power for

Street 1 (a normal ME4 class and two adapted classes, ME5 and ME6) and 2 levels of power for Street 2 (a normal ME5 class and an adapted ME6 class).
In addition, the use of the mesopic vision model allows the value of the maximum power levels to be decreased as shown in the table below:

Table 2 : active lighting classes on the pilot site

Speed category ($km \cdot h^{-1}$)	*Average traffic per hour (ATH)*	*Street 1*			*Street 2*		
		Classes	Power (W)		Classes	Power (W)	
			Photo	Meso		Photo	Meso
v > 60		ME4	107	94	ME5	93	79
30 < v ≤ 60	# < 292	ME5	70	60	ME6	55	45
	# ≥ 292	ME4	107	94	ME5	93	79
5 < v ≤ 30		ME5	70	60	ME6	55	45
v ≤ 5		ME6	43	33	ME6	55	45

The minimum safety power P_{min} is the minimum power provided by the combination of LEDs and the lamp driver, i.e. 11,3 W.
We can therefore establish the power transfer curves for each of the two streets according to the different speed categories.
The figure below shows the power transfer curves for the mesopic power levels.
In the first street (image on the left in Figure 3), where the street lights are positioned 30 m apart, a user driving at the maximum authorised speed (50 $km \cdot h^{-1}$) will always have ahead of him either 3 or 4 street lights (according to his intermediate position between two street lights) lighting the road at the maximum power for the activated lighting class (94 W or 60 W depending on the volume of traffic).
The change from minimum power to maximum power will occur gradually over a distance covering 4 to 5 successive street lights.
In the second street (image on the right in Figure 3, where the street lights are positioned 50 m apart, for a vehicle moving at 50 $km \cdot h^{-1}$, maximum power is maintained for the activated class over a distance covering 2 to 3 street lights and the increase in power is made over an equivalent distance.

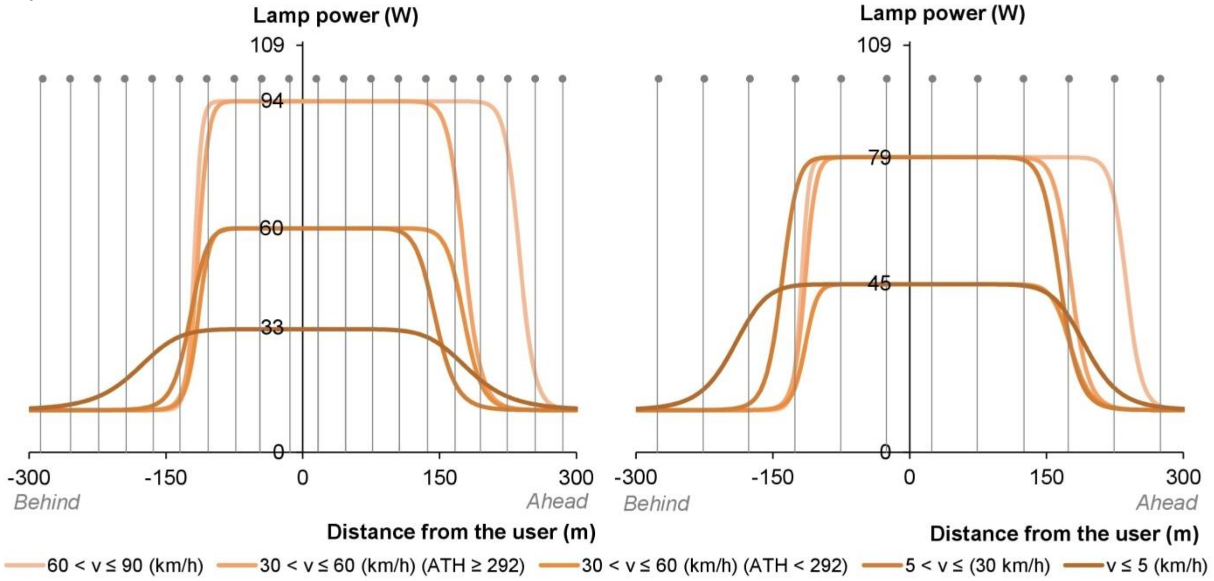

Figure 3 : Transfer curves for the first (left) and second (right) streets of the pilot site according to the speed and volume of traffic

NOTE: in the above two figures, the vertical bars represent the street lights.

On the basis of the calculation of average traffic per hour, we have estimated the duration of illumination of the street lights in each of the streets in a year. We have estimated the energy consumption of each of the street lights according to an identical constant speed for all users, according to the principle of transfer curves. The following figure shows the estimated consumption per speed category.
The combination of the mesopic model, LED lamps and intelligent management of the lighting system allows consumption to be cut to 23 % of current consumption of the site, i.e. a 77 % energy saving on average on all driving speeds

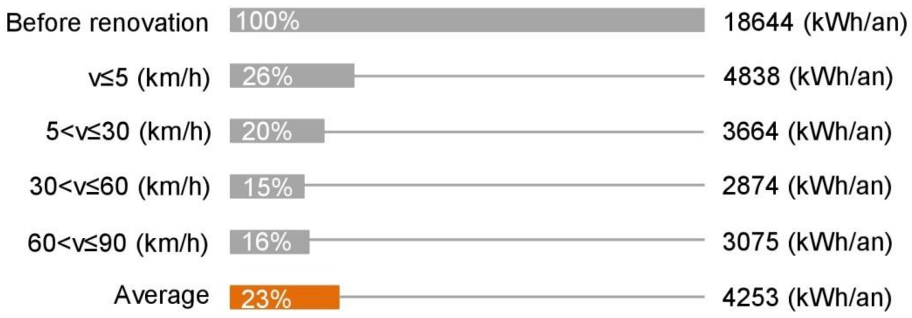

Figure 4 : Evaluation of the energy consumption

The above figure shows that using the mesopic model and driving at constant speed in the maximum authorised speed category (50 $km \cdot h^{-1}$ in our pilot site) allows an energy saving of 85 %.
The relative consumption of low-speed users is higher than that of motorised users because the intelligent lighting management model is developed in such a way as to increase their feeling of safety and their visual comfort by creating a more homogeneous luminous atmosphere.

Moreover, on average, at all driving speeds on the site, the distribution of the energy savings argues in favour of intelligent management of the lighting. Indeed, 81 % of the energy savings are attributable to the management model that we have developed.

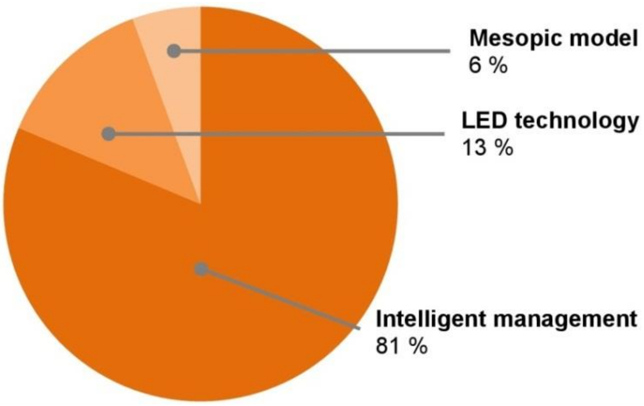

Figure 5 : Distribution of energy savings

4. Discussion

Combining the use of LED street lights and the mesopic vision model with an intelligent lighting management model allows significant energy savings to be made.
Until now, the dimming principles which have been tested offer opportunities for energy savings of between 20 % and 50 % (Europe 2007; Europe 2008).
However, to be the most efficient, intelligent management must be able to adapt the luminous flux of the street lights to the traffic conditions in real time.

The model we propose is based on the combination of two original power dimming principles in real time, spreading and the transfer curve. According to this model, the street lights automatically vary their power according to the progression of a user along the road. The street lights gradually increase in power according to a sigmoidal curve as the user moves closer to a street light. This dimming starts from a minimum safety power and increases up to a maximum power set according to the photometric requirements required by the lighting class actually activated. When the user has passed by the street light, it gradually decreases the power of the lamps as the user moves away from it, according to a curve that is symmetrical with that which controls the increase in power. A light signal thus follows the user along its path on the road.
In this way, the route is lit in the right place at the right time, in the right direction and with the right intensity, according to the movement of the user. Since a pedestrian is not a motorist, this system of intelligent management of the lighting provides a feeling of a light atmosphere, visual comfort and safety that is adapted to each user.

However, it is still too early to assess the true effectiveness of such a system since it is currently being tested and validated. In order to know what the real energy saving linked to the implementation of the transfer curve model is, the system must be monitored for a whole year. This monitoring has begun in March 2013 and the results will be communicated around June 2014.

Moreover, an assessment and acceptance by the local people of such a promising system must also be validated by field surveys. These have as their goals to test the values of the parameters defining the principle of the transfer curve and to evaluate the assessment by the local people of the varying levels of lighting. These surveys have begun in March 2013 and will be completed in December 2013.
In addition, the theoretical model of the transfer curve formulated by a sigmoidal function could not be implemented in its original form on the pilot site. The IT implementation of a model expressed according to a standard distribution requires the handling of too much data and this would endanger the correct functioning of real-time management of public lighting. A simplification has therefore been made to the transfer curve model when installing the system on the site: the change in dimming is not made sigmoidally but linearly. All the other axioms of the design of the model are preserved.

Be that as it may, the intelligent lighting management model that we are proposing offers opportunities for adaptation to different types of roads and paths: pedestrian routes, cycle paths, business parks, tunnels and underground passages, roads with reduced traffic at night etc.

Acknowledgements

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