Innovative sustainable development teaching at university: Study of lighting systems for safety bicycle rides

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Abstract: Numerous countries are nowadays trying to reduce pollution in the cities, in particular noise and CO_2 emission. New alternating means of transportation (other than cars) are now encouraged. Bicycle is one of those. However, one of the key points for promoting bicycles downtown is safety rides whatever the traffic and weather conditions. In that way, lighting systems are mandatory to been seen and to see correctly. Unfortunately, reliable technical data is missing. Only a very few commercial data is available on retailer's web site or in specialized shops. So, in this paper, we propose firstly a didactical scientific "cooking guide" for students, teachers and bicycle users, who want to choose and design their own lighting based on LEDs (light-emitting diode). Optical, thermal, electronic and power management aspects are discussed. And a set of basic answers to the following questions is provided: What is a simple way of measuring brightness? How does one choose an LED and its optics according to the desired lighting? How is the performance of an LED checked? How does one choose a heatsink? How is the regulation of one or more LEDs managed? Secondly, our didactical experience and feed-back of student's groups in our electrical department is reported and discussed.

Key-Words: Led, battery, bicycles, lighting system design and test, regulation intensity, dynamo.

1. Introduction

Urban (and extra urban) mobility is becoming a big challenge for a lot of local municipalities and district. Because of unbearable traffic congestion and pollution, they encourage citizens to use public transportation and also eco-friendly mode of transport. Bicycle is one among others. However, safety is most important point for riders. Thus, reliable and well sized lighting systems are mandatory. After some recalls of optic, thermic, electronic, some designs, based on LED, are presented as well as their performance and limitations. A comparison of different headlights is made with a study of glare. Finally, our teaching experience and student feed-back is reported and discussed.

1.1 Road signs and legislation

Road signs have letters 20 cm high in order to be read intelligibly at a distance of 100 m.
In many countries, bicycle lighting legislation must not exceed that of motorcycles [2]. For motorcycles, the power of halogen headlights is 55W with 2% declination at 0.8m height (to minimize glare), with 15W for the rear light and 20W for the brake light. Since LEDs have a consumption between 5 to 10 times smaller than filament lamps [8, 9], a bike should have a power of 10W at the front and 2Watt at the back to be seen, (3W in case of additional stop light).

1.2 Human eyes ability

The human eye can cope with varying levels of illumination, from 10^5 lux (a sunny summer day) to 2 lux (a full moon night). Nevertheless some minimum levels are required: for example 5 lux to move about, 150 lux for reading and writing [1].
The separating power of the eye is the limit angle of 0.017° below which two nearby bright spots can be distinguished. Legislation requires being able to see another vehicle at 150m. Therefore, the distance *d* separating two light points will be perceived at 150m by the following equation:

$$d = 150m \cdot 0.017° \cdot \pi / 180° = 5cm \tag{1}$$

We also can mention that the eye is sensitive to radiation of wavelengths between 400 nm (blue) and 700 nm (red). The energy flow of 1W at the wavelength of 555 nm (yellow green) is 673 lumen/W. On the other hand at 600 nm (orange), the flow perceived by the eye will be 430lumen/W.
Sensitivity of the eye is known as "spectral luminous efficiency".

2. Brief review of lighting

The relationship between luminous flux Φ (lumen) and luminous intensity (candela) corresponds to the following equation (2):
Φ (*lumens*)=*intensity(Cd). angle* $_{solid}$ *(Steradians)*

Steradian is a unit of 3-dimensional angular measurement. It is given by the equation (3) where θ corresponds to half of the total scattering angle (valid for angles less than 50°):

$$Steradian = 2.\pi.(1-\cos\theta) \qquad (3)$$

Illumination *E(lux)* on a small round surface is given by equation (4) with the measurement in lux between the outer and inner radius:

$$E(lux) = \phi(Lumen) / \left(radius_{out}^2 - radius_{in}^2\right)\cdot\pi \quad (4)$$

The figure 1 shows the typical relative illumination of a parabolic optic as function of angle.

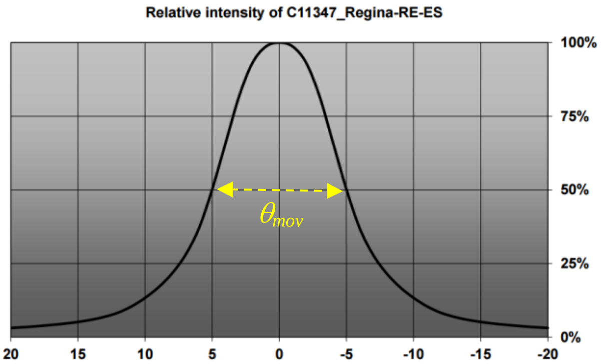

Figure 1: Relative illumination of a reflector with a medium illumination angle θ_{moy} =10° [11].

Therefore, one can simply project the luminous flux onto a wall at a certain distance to determine the angle of a parabolic reflector. Taking several measurements of the illumination on the wall one can find the number of lumens from the illuminated surface as can be seen in the figure [2]:

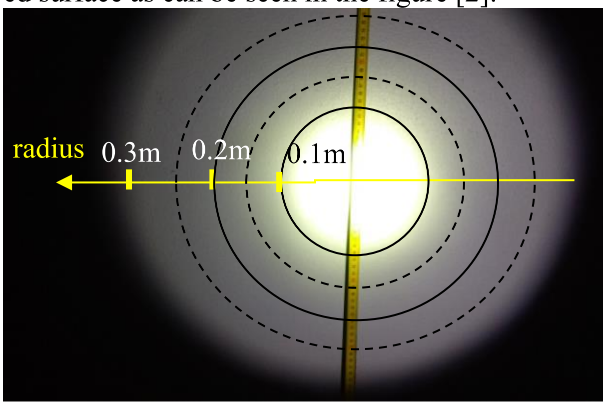

Figure 2: 11W flashlight at 0.5 m from the wall, the angle of the central optic is 9° with a second halo at 38°

Here, the measurement of *E* (in lux) on each circular slides (cf. figure 2), with a lux meter gives a total flux value of 1060 lumens, with a sampling radius interval of 5 cm:

$$\Phi = \pi\cdot\begin{bmatrix} 29.10^3\cdot(0.05^2-0)+17.4.10^3\cdot(0.1^2-0.05^2)+3500\cdot(0.15^2-0.1^2) \\ +1620\cdot(0.2^2-0.15^2)+975\cdot(0.25^2-0.2^2)+.... \end{bmatrix}$$

Theoretically, the illumination for a reduced and circular angle decreases according to the square of the distance between light and the place of measurement.

$$E_2(lux) = E_1(distance_1)\cdot\frac{distance_1^2}{distance_2^2} \qquad (5)$$

For example, if the lighting at 1m is 478 lux, at 1.66m, there will be only 172 lux as indicated in figure 3. The total illumination can also be written in the following way:

$$E(lux) = \frac{\phi(lumen)}{Surface(m^2)} = \frac{\phi(lumen)}{\pi\cdot(\tan\theta\cdot distance)^2} \quad (6)$$

Manufacturers define the medium angle θ_{moy} of reflector as the angle for which the illumination is *E/2*. The figure 3 shows the typical illumination of a parabolic reflector. Since the average angle θ_{moy} is used for this representation, we must be careful because the illumination is divided by 2 compared to the equation (6).

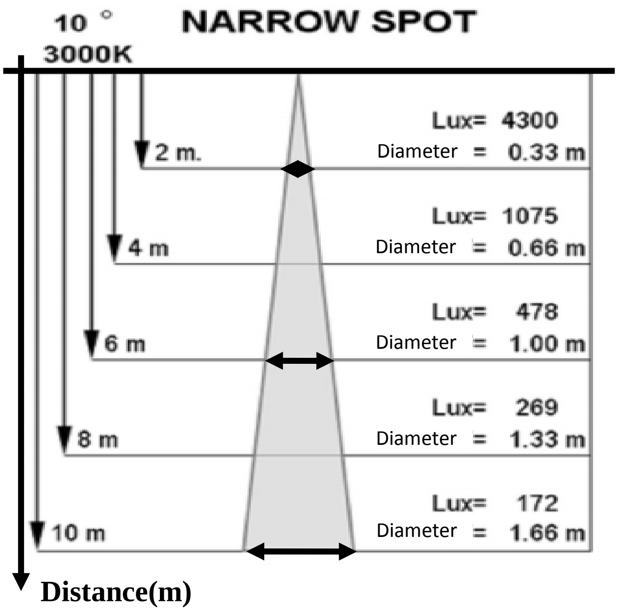

Figure 3: Illuminance for a medium angle θ_{moy} =10° aluminum reflector and for a flux of 991 lumen or 17200 Cd diameter 47mm * 44L, 85% performance [11].

Obviously, given equations (4), (5), (6) are valid only if the luminous beam shape is concentric and circular. The headlight reflector is logically a crucial element to generate a regular beam shape [12, 13].
On some headlights, the focal length of a converging lens may be shifted to select the angle of illumination for a desired distance.

3. Illumination and mapping

3.1 Measurement of illumination

To measure the illumination, a light meter is normally used. However, a smartphone can measure this value thanks to the light sensor needed both for its camera and for adjustments of the brightness of the screen according to external light. There is no need to use an accessory such as a Fresnel lens that focuses light by 160 ° to the sensor. But, the smartphone sensor must be oriented accurately in the direction of the light source.
In addition, depending on the sensor of the smartphone, a calibration check is required (cf. figure 4). From the figures 4 and 5, we can deduce the measurement errors of a Sony Z3 and an MIU4 XIAOMI using a reference lux meter, "tenma 72-6693" for example.

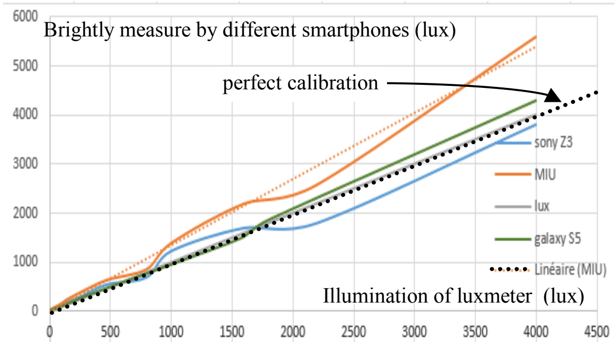

Figure 4: Calibration and performance test of luxmeter application of 2 smartphones [10] (used lux meter: "tenma 72-6693").

By zooming on the low value of the lighting (<100 lux) (cf. figure 5), one can estimate the discrepancy (offset) between the values given by the smartphones and the lux meter.
Once calibrated and errors manually corrected, it is thus possible for anybody to measure illumination with his smartphone.

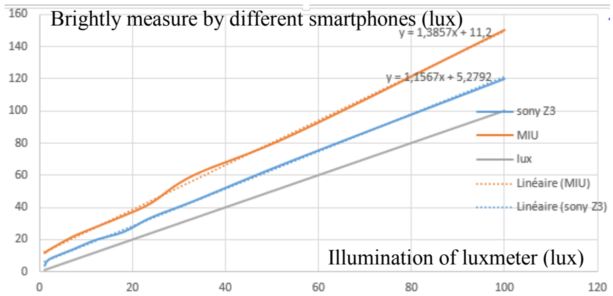

Figure 5a: Light meter performance test of smartphones.

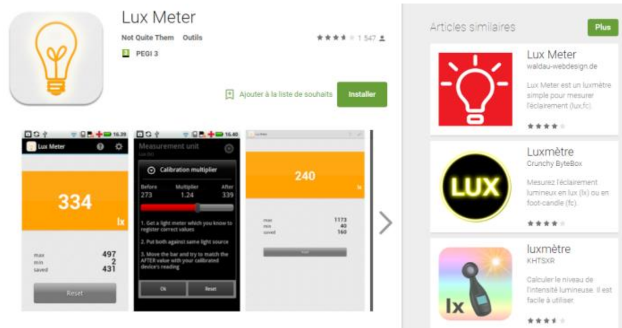

Figure 5b: Example of Android light meter application with calibration.

3.2 Mapping

For a vehicle's front light, a mapping of the illumination on the ground is required according to the inclination needed to light up the road. The headlight must obviously allow traffic signs to be seen without causing glare for other road users.
Mapping of a front light illumination can be carried out by hand by sampling many points. However, this mapping can also be done with a measuring device called a goniometer, as shown in figure 6.

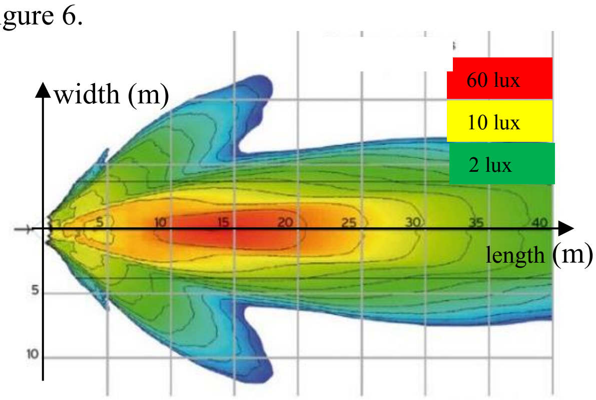

Figure 6: Mapping (in Lux) according to distance on the ground of a 3W bicycle light front with a special reflector (top view).

4. Power source of bike lighting

The available lighting power of the bike depends on the installed power supply (dynamo or batteries).

4.1 Dynamos

Since 2008, commercial hub dynamos (mass # 550g, price #90€) can provide a power of 3Watt with a yield of about 65% for speeds over 15km/h. the power generated by the dynamo being proportional to the speed, the dynamo must be connected to an "energy tank" which is often a super-capacitor of approximately 1Farad/5.5V. This energy storage makes it possible to maintain around 0.2W lighting power, during a "one minute stop" at a red light.

4.2 Batteries

Since 2010, the classical 18650 lithium elements (60g, 2.5A.h, 3.7V, 9.5W.h, internal resistance 0.1Ω), to deliver 3A) are often used to make bicycle lighting. This element is generally associated in series (S) to have more voltage or associated in parallel (P) to have more current.

For example, a 5A.h 3S2P battery contains 3 in-series groups each of 2 elements in parallel. Output voltage varies from 12.3V to 9V depending on the discharge.

With NiMH type AA batteries (3W.h, 30g), who have a quite high internal resistance (1.5Ω), the discharge current cannot exceed 0.25A to avoid warming risk. Therefore, such an accumulator can not provide high levels of power.

Large batteries (36V to 72V, 10A.h to 20A.h) for electric bikes can also power the lighting. In that case, a regulator must be inserted between this battery and LED lighting.

Lastly, since 2012, it is possible to use small lights (single led) to be seen (0.08W, 2€, 0.8lum, 19g) powered by 2 CR 2032 batteries (3V, 0.4€*2, 220mA.h, useful life 10h).

These 2 batteries can be replaced by rechargeable batteries for 2€ to 4.5€ (LIR2032=3.7V, 40mA.h, 2 Ω) but their lifetime drops to 2.5h.

5. Operating time with battery power

The disadvantage of battery power is the limit of the operating time, which depends on the power of the LED and the efficiency of the regulator. Operating time is given by the equation:

$$Time(h) = \frac{Capacity_{energie}(W.h)}{\sum Power_{absorbed\ LEDs} + Power_{controller}} \quad (7)$$

Since 2015 in Europe, the rear light may be flashing. This makes it possible to increase either the operating time or the power of the lighting during the time lit, if the resting time is known. The average power consumption is given by:

$$Power_{average} = Power_{light} \cdot t_{on} / T \quad (8)$$

Where t_{on} is the "light on" state duration and T the period.

6. Review of LEDs

A LED is characterized by its threshold voltage, its maximum current, its number of diodes in series (S) and in parallel (P), its maximum power, its emission angle, its brightness in lumens per watt, its thermal resistance , its spectrum, its CTC (Correlated Color Temperature: red, cold white, neutral white, or warm white). For example, there are 3 types of white LEDs, depending on the spectrum: cold (120 lm/W), neutral (110 lm/W), and hot (92 lm/W).

The table 1 compares different LEDs. LEDs that have more than 3 diodes in series are not considered : beyond 3, total threshold voltage becomes too high.

LED model / price	Configuration (S,P) Volt , A	size	$R_{TH\ JC}$	Flux lm/W
white 0.4€ 0.12W, 20°	1S 0P 3.3V, 0.04A	5mm		60
10W white 4 €, 120°	1S 0P 3.4V, 3A	Ø13.9 mm	2.5 °C/W	80 to 100
10W white 2 €, 120°	3S 3P 11V, 1A	Ø13.9 mm	2.5 °C/W	90 to 110
Led red 1€ 3W, 140°	1S 0P 2.5V, 1.4A	Ø13.9 mm	2.5 °C/W	70
Led red 0.3€ 0.07W, 8°	1S 0P 1.8V, 0.04A	10mm		10
Led RGB 0.2W, 120°	1S 3P SMD5050	5x5 mm		13

Table 1: Characteristics of different LEDs

Unfortunately, there are many copies for sale on the web with errors or wrong data sheets. Therefore, users must perform tests to check the real performances of the LEDs that have been purchased.

Some LEDs consist of an internal LED matrix [5].

For bike lighting, two types of LEDs are used:

- Low Power chip (less than 0.2 W)
- Power chips (1W to 10W).

The first type allows one to be seen but the number of LEDs needs to be multiplied and the second allow one to see. In the two cases, LEDs must be connected in series or in parallel according to the supply voltage or the regulator.
However, serial connection has one disadvantage: despite the very long lifetime of LEDs (#50 000 hours=50 times a filament lamp), if one of the Leds fails, all those that are in series do not work anymore too. Therefore, parallel mounting increases the reliability of the lighting system.

Ribbons or flexible divisible LEDs include only 3 low power LEDs in series, a resistor to limit the current, to be supplied under 12Vdc.
Self-adhesive LED ribbons (66 LEDs per meter, 12V, 0.4A/m, 12€/m, 120°) are able to illuminate a large surface but are not the most suitable for bike lighting applications.

We can finally notice that 3-color LEDs (RGB) used to make white, are not very bright. We do not recommend them for bicycle lighting.

Lastly, it should be mentioned that luminous flux increases with the current. But, flux saturation occurs roughly for current higher than 40mA. Thus, for diodes with current around 20mA, there is no interest to bias it beyond the nominal value.

7. Led power and heat dissipation

When LED power is greater than 0.2W, a heatsink is required to dissipate the heat. Otherwise, the junction temperature of the semiconductor could exceed 150 °C and destruction of the component occurs. When heatsink is mandatory, one must take into account its shape and mass. Indeed, they are critical criteria for bicycle propelled by the human power. Thus, design or choice of an efficient heat sink results from a compromise between mass, shape and thermal performances.

7.1 Thermal modelling

Figure 7 gives the thermal equivalent diagram of the LED+heatsink+temperature sensor assembly, in steady state conditions. It is derived from the generic model (cf. figure 8), of course without insulator, PCB, baseplate.

Where:
T_J is the LED junction temperature,
T_{amb} is the ambient temperature,
Rth_{jc} is the thermal resistance junction-case,
Rth_{CH} is the thermal resistance case heatsink,
Rth_{HA} is the thermal resistance heatsink-ambient,
P is the heat power across the diode.

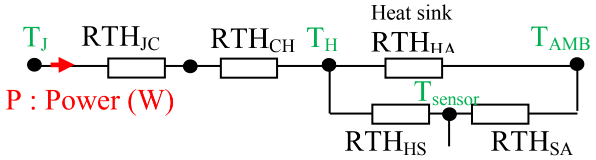

Figure 7: Thermal model of a LED, heatsink and temperature sensor [5].

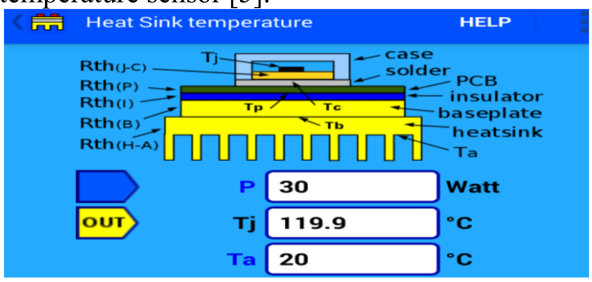

Figure 8: Android application « PCB thermal calculator »

From the previous thermal model, and neglecting the impact of sensor, the relation between temperature, thermal resistances and power P is (9):

$$T_{jonction} - T_{Amb} = (RTH_{JC} + RTH_{CH} + RTH_{H.Amb}) \cdot P$$

The heatsink temperature can be determined by the following equation:

$$T_H - T_{Amb} = RTH_{H.Amb} \cdot P \qquad (10)$$

The heat resistance of the sink can be determined by software but also by curves and charts found in data sheet. This value depends mainly on the convection conditions, shape and geometry of the heatsink, surface, type of heat loss… So, experimental test is often necessary to refine the value. With natural air convection, the thermal resistance of a vertical aluminum plate corresponds approximately to the equation (11) with the well-known experimental value $h \approx 10 W.m^{-2}.°C^{-1}$.
(Note that with fins, this coefficient can rise up to $80 W.m^{-2}.°C^{-1}$).

$$RTH_{H.Amb} \approx \frac{1}{h \cdot Surface(m^2)} \qquad (11)$$

Figure 9 shows that it is not worthwhile to have a large heatsink length because, beyond 50mm, Rth do not decrease anymore significantly.

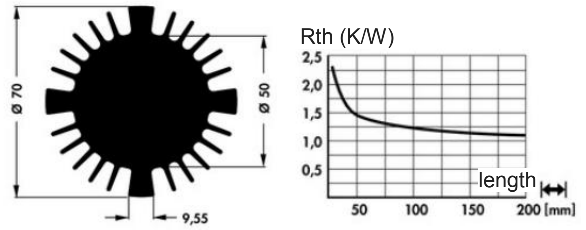

Figure 9: Axial Heatsinks for LEDs SK 570 (top view)

7.2 Retrieving the main thermal data

Manufacturers give the derating current curves. It means that maximum allowable current in the LED decreases with the rise of the ambient temperature. An example is given in figure 10, with several curves corresponding to different LED/heatsink assemblies. Surface under curves is known as Safety Operating Area (SOA). The maximum operating temperature junction T_{Jmax} corresponds to the "star" dot on figure 10. Here, we read:

$$T_{Jmax} = 150°C$$

The values of the total thermal resistance Rth_{JA} (junction to ambient) can be also retrieved.
For example, for a 10W led, taking the 2 black dots P1 and P2 on the light blue curve, we read:
- The maximum current I_{max} =3A at T_{Amb_max} 35°C and:
- A reduced current I_{red}= 1A at T_{Amb} 115°C).

Knowing the threshold voltage of the led, (#3.3V at 35°C and #3V at 115°C), we calculate power in P1 and P2. The value of $Rth_{JA} = \Delta T/\Delta P$ is then roughly deduced. Here, Rth_{JA} # 11 °C/W.
It can be also confirmed by Equation 12.

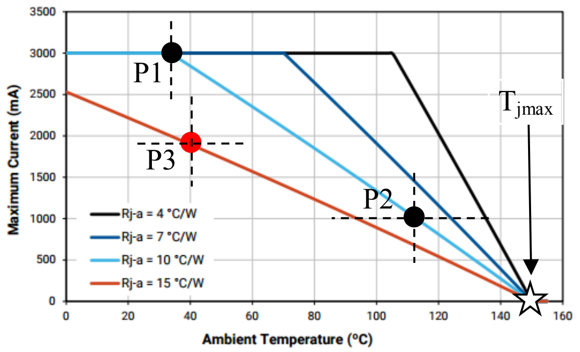

Figure 10: Maximum available current of a white LED 10W as a function of T_{amb} and the heatsink.

Conversely, for a given Rth, the maximum current of the LED can be determined from the ambient temperature. (Example red dot P3 in the figure 10 with Rth_{JA}=15°C/W).

$$I_{forward}\ max = \frac{Tj - Tamb}{R_{TH_{JA}} \cdot V_{seuil}} = \frac{150-115}{10 \cdot 3.25} = 2.2A \quad (12)$$

Note: The smaller the Rth_{JA}, the higher the ambient temperature may be, but the larger the heatsink will need to be.

7.3 Heatsink temperature measurement

Knowing the power supplied *P* to the LED and the temperature $T_{heatsink}$ of the heatsink [17], the junction temperature can be estimated from the equation:

$$T_{jonction} = T_{heat\,sink} + RTH_{JC} \cdot P \quad (13)$$

To not exceed the maximum temperature of the LED, the temperature can be measured and monitored by a sensor stuck on the heatsink. For example, a linear sensor LMx35 (To92 case) provides a voltage of 10mV/°C. However, an offset between the sensor measurement T_{sensor} and the real temperature of the heatsink $T_{heatsink}$ does exist due to the inherent thermal resistances of the sensor case: $RTH_{Sensor-A}$ (sensor to ambient #140 °C/W) and RTH_{HS} (sensor to heatsink #30 °C/W) (cf. figure 7 and 8). Response time of this sensor can be neglected compared to heatsink time constant.
Thus, the actual temperature of the heatsink T_H as a function of the temperature of the sensor housing is given by:

$$T_{heat\,sink} = (T_{sensor} \cdot (1 + \frac{RTH_{HS}}{RTH_{SA}}) - \frac{RTH_{HS}}{RTH_{SA}} \cdot T_{amb}) \quad (14)$$

Example: If the measured temperature is 53°C with an ambient temperature of 20°C, then the real temperature of the heatsink will be 60°C.

If the sensor case was a To220 (instead of To92) then $RTH_{Sensor-A}$ would be 90°C/W (instead of 140°C/W). Moreover, this kind of case makes it possible to minimize the contact resistance with heatsink at 4°C/W. Then, the gap between temperature measurement and real heatsink temperature becomes very small. It is thus no more necessary to make correction with equation (14).

Lastly, an infrared thermometer makes it possible to check this difference between the measurement of the sensor and that of the cooler.

7.4 Other thermal considerations

Unfortunately, it is not possible to install forced ventilation (with fan) on a bike, to minimize the size and mass of the heatsink.
However, the natural movement of the bike helps to cool the bike's lighting. So depending on the speed of the bike, it would be possible to adapt the light output and illumination according to the temperature of the heatsink with a feedback control loop.
Many bicycle lights are made of thermoplastic polymer, which is easy to mold and therefore light. But plastic does not allow for effective heat removal compared to an aluminum case. In addition, the aluminum case will be more robust to mechanical shocks but will be more expensive to machine.

8. Rear and front lighting

Required LED power for rear and front lighting depends on weather and external ambient light conditions. Specifications and needs are different since rear light is used “to be seen” while the front light is used “to see”.

8.1 Rear lighting

For rear light, vehicle lighting must be visible at 150 m. The optics of the rear lighting is important: an angle of 6° will ensure greater visibility from a distance.
- 10 red LEDs of 30 mA (0.6W total) are enough for lighting at night in normal conditions.
- When there is fog during the day, power must be increased up to 2W.
- At least, during sunny days in summer, it will take a power of 3W in case of additional brake light, (to warn a person behind the cycle). In that case, the brake light can be triggered by the brake lever or by an accelerometer that will act by detecting each deceleration.

8.2 Front lighting

Front light must be sized to fit a worst case: A bike can easily reach 15m/s (i.e. 54km/h) into downhill. Since human reaction time is around one second, the front light must reach 15m at least to illuminate the road and the roadside in order to avoid a potential obstacle [6].
Let consider a design example:
Powerful 10W LEDs all have a half angle Θ of 60°. Thus, a reflector is used to reduce Θ to a value often lower than 10°. Light beam is then focused for a better illumination of the road. The reflector is often made of aluminum. This allows the heat to be pushed outside.
The LED is mounted on a 170g cylindrical heatsink of diameter 45cm and length 5 cm. Its thermal resistance is RTH_{HA} # 9.6°C/W. Moreover, thermal resistance junction-heatsink is RTH_{JH}=# 0.625°C/W. Therefore, in first approximation, the temperature rise $Tj-T_{Ambient}$ is #102°C (96°C+6.2°C) for an absorbed power P_{abs} of 10W.
In fact, to be more precise, we must consider the power efficiency $\eta_{led} = P_{light}/P_{abs}$ of the led. Indeed, absorbed electrical power P_{abs} is equal to:

$$P_{abs} = P_{heat} + P_{light}$$

Where:
P_{heat} represents heat losses and P_{light} the useful lighting power.
Thus, we can write:

$$P_{heat} = P_{abs}(1 - \eta_{led})$$

And we obtain the maximum ambient temperature:

$$T_{Amb\,max} = T_J - (RTH_{JH} + RTH_{HA}) \cdot (P_{abs} - P_{light})$$

That is:

$$T_{Amb\,max} = T_J - (RTH_{JC} + RTH_{CA}) \cdot P_{abs}(1 - \eta_{led})$$

Thus, in our example, for a maximum safety margin, we chose a maximum junction temperature of 100°C. Assuming η_{led} roughly equal to 30%, the ambient temperature can reach the maximum value:

$$T_{Amb}\,max = 100°C - (0.625 + 9.6) \cdot (10W \cdot 70\%) = 28°C \quad (15)$$

Lastly, we can mention that the luminous flux (and thus η_{led}) decreases slightly when the temperature increases (cf. figure 11). However, this not significant since the natural movement of the bike cool down the lamp when riding.

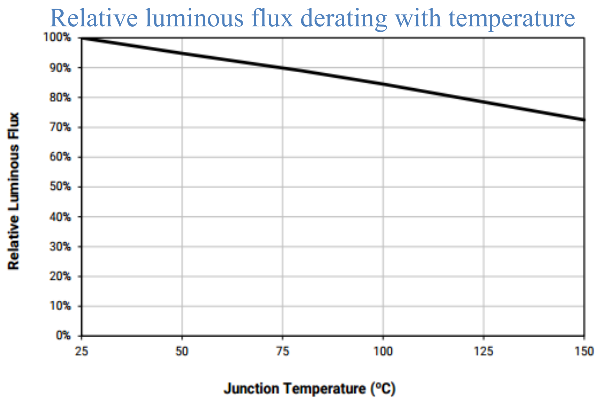

Figure 11: Relative lighting flux decrease as function of temperature Tj [7].

But what current is needed to have the number of lux at the desired distance?
The flux is almost proportional to the current as indicated in the figure 12:

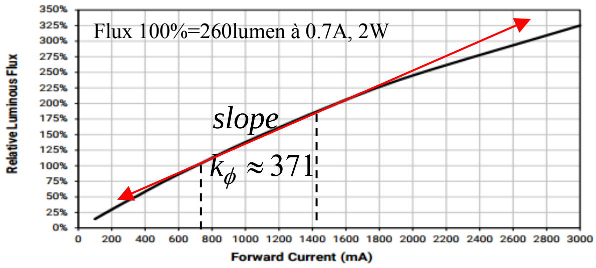

Figure 12: Relative light flux vs. current [7].

With an “in-series” LED configuration and a number of LEDs nbr_{led}, we get the following equation:

$$I_{Forward} = \Phi/(k_\Phi.nbr_{led}) \quad (16)$$

Replacing ϕ from equation (6) and using θ_{moy} angle (cf. §3), we obtain (17):

$$I_{Forward} = (2 \cdot E \cdot \pi \cdot (distance \cdot \tan\theta_{moy})^2)/(k_\phi \cdot nbr_{led})$$

Example: if an illumination of 70 lux at 20m is needed, with four LED in series and a reflector of 5° (medium angle), the lighting radius is 1.75m with an area of 9.76 m^2. The current is calculated with (17):

$$I_{Forward} \approx (2 \cdot 70 \cdot \pi \cdot (20 \cdot \tan 5)^2)/(371 \cdot 4) = 0.9A$$

Knowing the threshold voltage $V_{Forward}$ as a function of the current, we can deduce the absorbed power. At first order, for 0.2A< $I_{forward}$ < 3 A, and for a white LED [7] at 25 °C, we have:

$$V_{Forward}(0.9A) = 2.73 + 0.192 \cdot I_{forward} = 2.9V \quad (18)$$

And the total electrical power P is:

$$P = nbr_{led}.V_{Forward}.I_{Forward}$$

Here:

$$P=4.(2.9).(0.9)=10.45W$$

To improve the efficiency of lighting η_{led} without increasing the electrical power within a given space, i.e. for a particular heatsink, an increase in the number of LEDs is often resorted to (3 LEDs of 3.3Watt instead of one 10W LED). In that case, physical diameter rises from 22mm to 55mm. For 4 LEDs the diameter will be 50mm and for 7 LEDs 68mm.

9. DC/DC Converters

Front lighting needs depends strongly on external conditions; it requires significant light output at night, but only a light output roughly divided by 2 in case of foggy weather. Luminous flux might be adjusted by varying the LEDs current. For that purpose, high power efficiency DC/DC electronic converters can be used. Possible structures are discussed in §9.1, 9.2, 9.3, 9.4.

9. 1 Constant current mode converter

Constant current regulation requires a shunt resistor in series with the LED and feedback [8]. Often, the commercial IC’s allow for a variable setpoint (analog dimming or Pulse Width Modulation, PWM). Otherwise, the measured value of the constant current must be changed by changing the shunt resistance value.

Figure 13 shows the principle of a current regulator with PWM. The input voltage V_{in} is chopped by MOS transistor Q_1. Depending on PWM duty cycle, we obtain a mean voltage V_{DL} across the free-wheeling diode DL. Current across inductance is filtered to have an average DC current in the LED D_1. The feedback and the PWM oscillator are managed by an integrated circuit. The capacitor C_L reduces slightly the current ripple (10%) in the shunt resistor R_1.

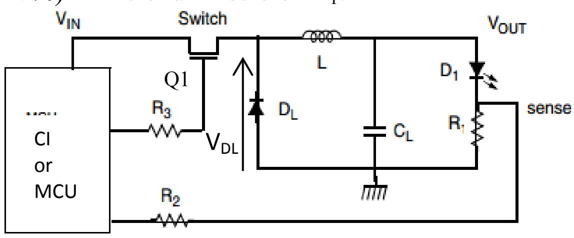

Figure 13: Step-down converter (current regulation).

9.2 PWM controler

Figure 14 shows a converter where the switch transistor is inside the integrated circuit.

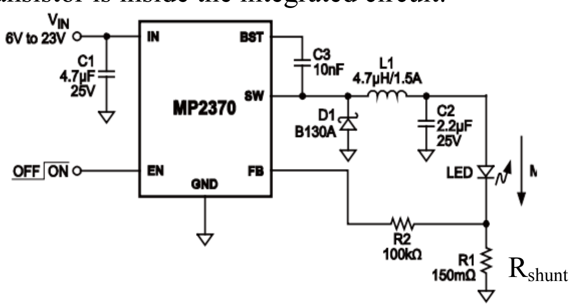

Figure 14: Step-down controller (current regulation).

Figure 15 depicts the internal functions of the MP2370 including the oscillator t(o create the PWM signal) and all circuits for the current regulation.

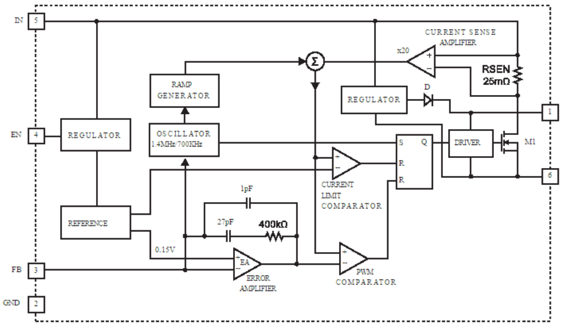

Figure 15: Block diagram of MP 2370.

The previous circuit is used to regulate the current with a constant PWM frequency and fast regulation. But it is possible to exert control by a simple comparator that has a hysteresis.

9.3 PWM/Hysteresis controler

Pedagogically, this is the one that offers the simplest way to study the converter, and besides didactical kits are available [15]. A schematic is given in figure 16.

Since the comparator U1A cannot drive enough current to switch properly the power MOS transistor Q_1, a simple push-pull stage (Q_2 and Q_3) is inserted.

Then, the circuit operates as follows:

When Q1 is turned "on" current through the shunt resistor R1 increases till I_{max}, the upper value of hysteresis. Then, the transistor Q_1 is switched "off" and the current decreases thanks to the freewheeling diode. When it reaches the lower value I_{mini} set by the hysteresis, Q1 is switched "on" again.

The threshold values I_{max} and I_{mini} of the hysteresis are given by the following equations:

$$I_{max} \cdot R_{shunt} = \frac{(R4+R3)}{R3} \cdot V^- \tag{20}$$

$$I_{mini} \cdot R_{shunt} = \frac{(R4+R3)}{R3} \cdot V^- - \frac{R4}{R3} \cdot U\,sup\,ply \tag{21}$$

With a small hysteresis, the average current in the LED will be:

$$I_{average\,led} \approx (I_{max} + I_{mini})/2 \tag{22}$$

However, it must be noticed, with this kind of circuit design, that the switching frequency is not constant: it depends on the hysteresis cycle. But this frequency must remain into a defined range 20 kHz-200 kHz. The upper limit is given by physical limitations of the MOS transistor while the lower limit is set up to avoid an unpleasant whistle that could be heard by the human ear.

Here, the switching period T_{pwm} is obtained by the following well-known equation:

$$T_{pwm} = L \cdot \Delta I \cdot \left(\frac{1}{U_{sup\,ply}} + \frac{1}{voltage_{threshold} + 0.6}\right) \tag{23}$$

Where the current difference ΔI is given by equation:

$$\Delta I = I_{max} - I_{mini} = \frac{R4}{R3} \cdot \frac{U_{sup\,ply}}{R_{shunt}} \tag{24}$$

From equations (23) and (24), it can be observed that the switching frequency will depend strongly on the supply voltage, but also on the inductance.

The average voltage V_{shunt} across the measuring shunt resistor is chosen relatively low (around 0.3V) to avoid losses.

Therefore, the value of the hysteresis is determined to be less than half V_{shunt}, i.e. 0.15V. Finally, the value of the inductance is chosen to have the highest possible switching frequency to minimize its volume.

The current in the LED, can be easily increased by controlling the voltage V^- with the adjustable resistor RV1, but care must be taken not to exceed the current limit values of the transistor, the inductance, diode and the shunt resistance.

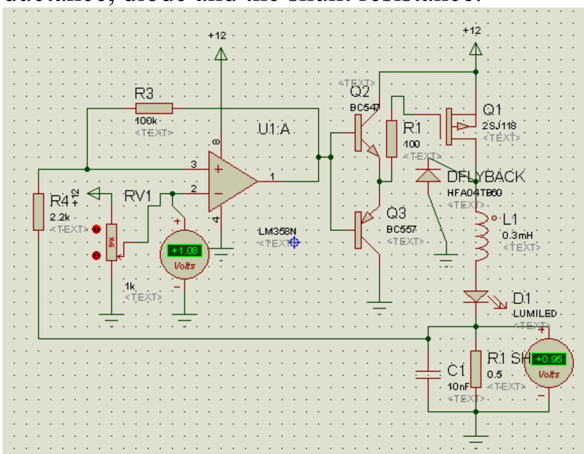

Figure 16: PWM hysteresis converter schematic.

For low power lighting such as breakable LED ribbons, motorcycle turn signals ... a current limiting resistor is used with a constant power supply of 12V. Structure of this type of converter is detailed in §10.

9.4. Voltage controlled DC/DC converter

If we want to use lights initially designed for motorcycles, a 12V constant voltage power supply must be created from an electric motor bike battery (24V, 36V or 48V). This 12V voltage is then used to power the rear LED strips, but also a USB converter 5V/2A for a smartphone.

Normally, the current regulators described in §9 do not operates directly from the 48V power supply of an electric bicycle battery, because the duty cycle of the PWM becomes too low to offer good sensitivity in the regulation. In that case, voltage controlled DC/DC converters must be used.

For this kind of structure, the feedback is made on the output voltage with a resistance divider bridge R2, R1, as can be seen in the figure 17. Returned voltage is compared to a 1.25V internal reference voltage. Therefore, by varying the ratio of the resistors R1, R2, the converter output DC voltage U_{supply} can be set to the required value. It can be observed that the value of the output capacitor C_{out} is 100 times greater than for current regulation. Indeed, this capacitor makes it possible to filter the residual fluctuations due to switching frequency but also the variation of the output current.

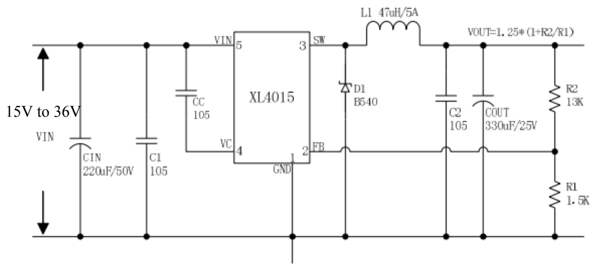

Figure 17: Typical diagram of a step-down chopper in voltage control mode, with internal switching transistor 12V 4A.

If the DC converter output voltage U_{supply}, has been chosen to be close to the threshold voltage of the LEDs matrix, a serial resistance R makes it possible to limit the current through the LEDs without too many losses.

The resistance R is given by:

$$R = \frac{U_{supply} - U_D \cdot nbr\_led\_serie}{I_{limitation}} \qquad (25)$$

And the power loss in R is:

$$Powerloss = (I_{limitation})^2 \cdot R \qquad (26)$$

This solution is generally used for LEDs that are powered by currents below 40mA.

But even for large 3A currents, the efficiency remains acceptable as can be seen in the figure 18.

The current, the power absorbed, the losses in the resistance, 4 white LEDs (cree company) and a 12V supply can be observed as a function of the resistance.

However, we must pay special attention when using such a constant supply voltage DC converter.

Indeed, the LED threshold voltage decreases as the operating temperature increases [5]. This reduction is approximately 0.15V between 25°C and 125°C. Forward voltage across LED as a function of temperature, can be modeled by equation (27).

$$V_{Forward}(T_J, I_F) ; \; 2.73 - \frac{0.15}{125-25} . (T_J - 25) + 0.192 \cdot I_{forward}$$

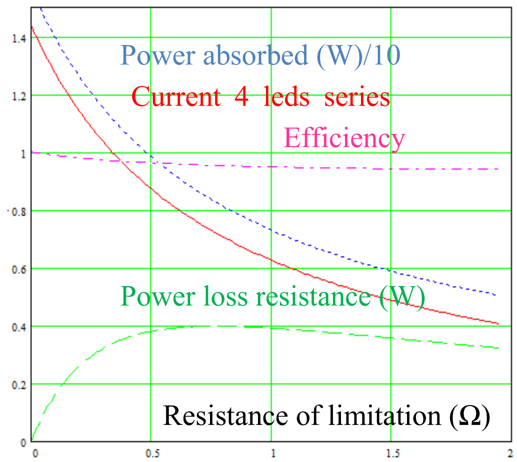

Figure 18: Measurement of the performance of the led power supply of 4 Cree leds [7] with a variable resistance in series 0 to 2Ω [10].

This temperature drift leads to a possible cumulative divergent effect and destruction of diode, if nothing is done. Here, the serial resistor, not only limits the current, but also acts as temperature feedback to stabilize the current bias point. A minimum voltage drop (several 100mV) across the resistance is recommended to be efficient.

Thus, voltage regulation and current regulation modes have their own advantages. However, the current regulation avoids the risk of thermal divergence and seems to be more suitable than a voltage control for lighting control applications.

10. Performance of DC/DC converters

To improve the autonomy of lighting system, it is necessary to optimize performances of each part.

In particular, losses in DC/DC converters must be checked: firstly, it is preferable to choose the switching frequency at the lower limit (#20-40kHz), because losses increases with the switching frequency. Secondly, a typical controller IC consumes permanent quiescent current (30 to 40mA). Therefore, there is an almost constant power loss in the DC/DC converter. Typical efficiency is around 90% for a range of currents as can be seen in the figure 19.
Moreover, it can be observed that the efficiency decreases slightly when the input voltage increases (because of the current consumed by the IC).

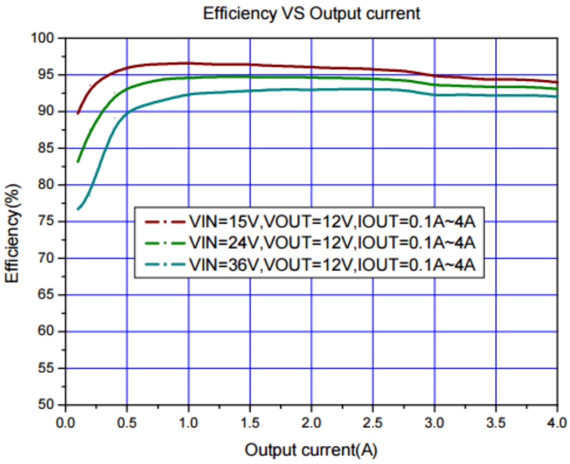

Figure 19: power ratio of 12V/4A XL4015 DC/DC converter.

11. Bike lighting protection circuit

A fast fuse (CMS) at converter input is necessary to protect the power source against electric problems. A thermal protection is also required against overheating in LEDs case. A bimetallic thermostat (thermal switch or cut off) is an effective solution. This thermostat - known variously as "switch", "thermal fuse", "thermal switch", etc.- cuts the power supply if the temperature measured on the LED heatsink becomes too high. These switches are resettable with a temperature hysteresis of 20°C.
We can find these protection circuits for a few euros. There are many brands, for example ksd97000, ksd01F, JUC31F, AIRPAX, Multicomp, Klixon, Selco, ESKA, etc.

12. Test of various headlights

Very few manufacturers give the specifications of their LED lighting systems although this would allow an accurate knowledge of the power emitted and the power lost. It is therefore often necessary to test, to know characteristics and limits of the systems. So, we have tested 4 commercial headlights of different powers with parabolic reflectors. Results are summarized in table 2. Configurations, structure are compared according to the number of LEDs, the size, the mass, the optics, the efficiency of the converter and prices.

number of LED & config	1S Current regulation	4 Current regulation	4S Voltage regulation	7P Current regulation
Size L*Ø (cm)	14*4	6.8*10	5*5	6*6.8
Mass	150	170	170	255
Angle of reflector (°) and lumen	5.7° 450Lm 31° 52 lm	5.7° 345Lm 31° 243 lm	9° 775lm 38° 384lm	11° 1400lm 45° 420lm
Total flux	500 lm	588lm	1160lm	1820lm
Lumen/watt	112	106	106	120
Power supply	4.4W	9.3W	16.8W	20W
LED Power	4 W	5W	10.9W	15W
Converter Efficiency	90%	53%	64%	75%
RTH_{HA} °C/w	5	2.7	9.6	2.8
ΔTemperature heatsink	20°C	25°C	106°C	42°C
Input Voltage	4.2V to 3V	12V to 80V	8.4V	6V to 30V
Price light	50€	10€	12€	30€
battery ref 18650 Price	1S 3€	2S2P 13€	2S2P 13€	2S3P 20€

Table 2: Headlight features, neutral white.

12.1 Comments

From our experimental tests, we can make some comments:
-The price of lighting is not a guarantee of quality because it is based on the number of sales and the seller's margin.
- If the lithium batteries are totally discharged (100%), then, the battery dies whatever the headlight.
- When recharging, a BMS (battery management system) rebalance the series elements [14].
- Only the first head light "1 led lighting 1S" turn off by itself in case of too low battery level detection.
- None of the four tested lighting systems has temperature sensor and protection against overheating.
- Luminous flux (lumens) has been reported in the table according to information given in §13.2.

12.2 Results extraction

The flux (number of lumens) produced by 2 among the four selected and tested lights has been obtained from curves given in figures 20, 21 and reported in the table 2.

Figure 20 shows the illumination on a wall at a distance of 0.5m (circular spot). From these curves and using equation (4), the value of the flux is easily extracted with a spreadsheet.
The decrease of the lighting according to the distance from spot center (or angle of reflector) is "almost" linear around the center. It means that there is the circular glow. This is why, the number of lumens is given for two angle values and circular slides (cf. figure 2), in the table 2 and there is a zoom of the scale on the curve 20.
In addition, this measurement also makes it possible to determine the average angle of the reflector as indicated in figure 1.

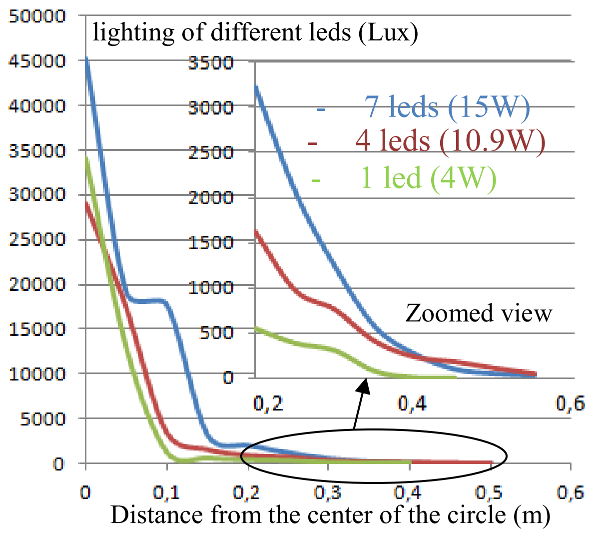

Figure 20: Illuminance for 3 lamps at 0.5m from the wall depending on the distance from the center

Figure 21, gives the illumination at ground level of the 7LED 1820lumen lamp placed at two different heights: 1m and 0.7m as well as the 1 LED lamp of 550 lumens inclined so as to illuminate from 13m away.

It can be observed that the power is greater at ground level, when the lamp is lower. This is obvious because the ellipse drawn on the floor is smaller.

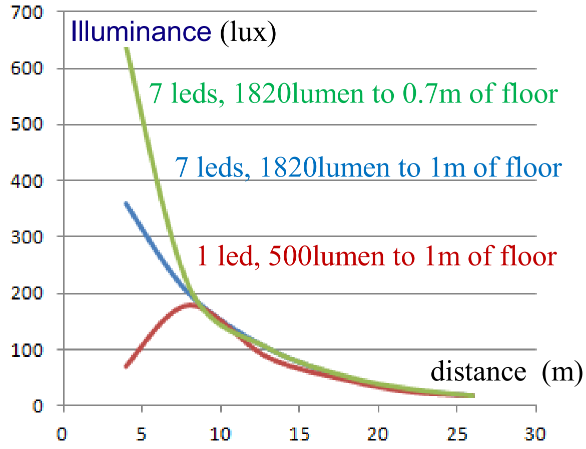

Figure 21: Illuminance at ground level according to the distance of the light source.

It can be seen that a lamp with a reflector with a small angle, allows the illumination of the chosen part of the road.

Figure 22 shows the illumination at a height of 1.75 m as a function of distance, in order to detect whether a pedestrian or another cyclist will be dazzled (or not) in the center of the beam. If we shift 1m towards the near side a decrease of 10lux still needs to be made.
Therefore we can conclude that at 25m far, the illumination (7 leds lighting) of pedestrians is relatively low but they will be seen and will not be too much dazzled.
At the opposite, the "1 LED lighting" with a small angle is not enough to see obstacles and roadsigns at 25m. This is not acceptable, compared to 7 LED lighting.

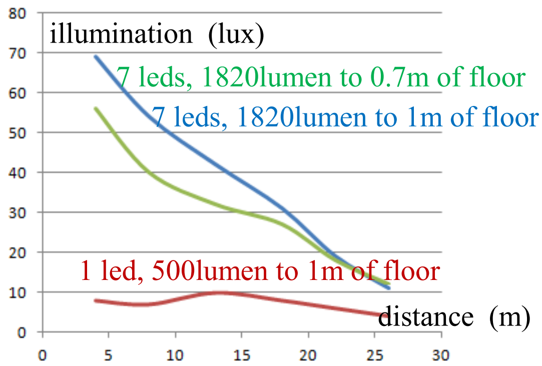

Figure 22: Illuminance at 1.75m height (eye height of an adult) depending on the distance of the light source.

Finally, we must take care of glare: to minimize glare at night, instead of taking a parabolic reflector, it is possible to use a reflector that creates an elliptical-shaped ground surface. In that case, the

large radius must match the width of one vehicle; so, 1meter for a bike, but often a value of 2 to 3m is set to see also the roadside.
On the subject of glare, all drivers know that you should not look the on-coming vehicle but look away from it and rather follow the line on the near-side of the road.

13. Didactical experience

13.1 General organisation

Our "University Institute of Technology" added in the student's cursus, sustainable development aspects in early 2010. In particular we started to work on eco-friendly mode of transport and electric vehicle design. It was and it always is an innovative and original didactical approach since only a few universities works on similar topics.
Each year, students work on this topic and have successively interest for the different technical aspects: mechanical, electrical, embedded equipment, wireless communication etc.
This year, thematic was thus electrical bicycle lighting. Project was scheduled over one full academic year. (One module of 40 hours per year). All the students (around 50) of second year study participated. We adopted a « Learning by project » strategy strongly connected to theoretical courses. Tasks were divided in order to work by pair. The design approach previously described in this paper was used as "cooking guide" to help students during the project.

13.2 Student's feed-back and assessment

At this end of the year, a opinion poll is done to get the student's feedback and satisfaction rate. Answer rate was almost 90%. Among the collected information, we can mention the most significant ones:
- Global satisfaction rate was around 80%
- All the students reported difficulties because of the lake of technical data. So, our guide was very useful.
- 85% estimate the subject had a high "complexity" level because the mix of technical aspects (optical, thermal, power electronic, mechanical …)
- Almost all students say that they learn a lot from a technical point of view but also work organization and project management.
- 64% say that they are now better sensitized to the sustainable development needs and convinced of eco-friendly transport necessity.

13.3 Future work

Defining a design strategy for lighting systems with a set of precise performance tests was the initial goal. Studies are now in progress to better control lighting and the management of batteries using a small processor to minimize the price such as Arduino nano [18].
All the presented work should help to define national and European standards in the near future in collaboration with association and biker federation.

14. Conclusion

Future development of eco-friendly transportation modes is possible only if the safety of users is guaranteed. Bikers are particularly vulnerable and fragile on roads. Optimized lighting systems are obviously mandatory.
While lighting manufacturers give only some commercial information, this paper provides "a cooking guide" with examples, qualitative and quantitative data to help students, teachers, and users when they want to design or to choose their own lighting system. The design of bicycle lighting system has been discussed. LED characteristics, optical, thermal and electronic aspects have been presented and investigated. Impact of battery, heat sink and DC/DC converter on light power limitation and efficiency has been explained.
Fortunately, many bike clubs are permanently carrying on lighting tests to help users make valid choices [16, 10].
Finally, we hope that will help to promote all year-round the use of the low-energy and health-friendly vehicle.

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