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Energy Saving Potential of Traffic-Regulated Street Lighting

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Abstract: Some municipalities switch off street lights for several hours at night to save energy and reduce operating costs as a consequence of soaring electricity prices in Europe. Complete darkness in the streets raises public concern about safety and security. The current street lighting standard EN 13201 enables the road luminance to be reduced in parallel with diminishing traffic volume offering a viable tradeoff between energy saving and road safety. This paper presents a methodology to estimate the energy-saving potential of traffic-regulated street lighting based on traffic counting data. By analyzing traffic volume and composition collected from an urban street over the one-year period, we found that traffic sensor-regulated street lighting can deliver up to 55% reduction in electricity costs while maintaining road luminance in line with the recommendations of EN 13201-2. In the presented case, the daily traffic volume profiles were remarkably stable following either a workday or a holiday pattern. Statistical analysis showed that 45% energy saving could be achieved by the pre-programmed dimming schedule of the luminaires while remaining compliant with the standard. The effect of daylight-saving time on the energy consumption of adaptive street lighting was also analyzed.

Keywords: traffic counting; energy saving; adaptive lighting; dynamic lighting; dimming schedule

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1. Introduction

Energy prices in Europe have risen to an unprecedented high level since 2021[1]. The detrimental consequences of Russia's war on Ukraine pushed up wholesale electricity prices more than ten times relative to the average of previous years by August 2022 [2]. Although prices dropped from a record high level in the fourth quarter of 2022, market players are counting on steadily high energy costs in the long run. To reduce electricity bills, municipalities throughout Europe switch off street lights for a couple of hours during the night [3]. Although scheduled darkness reduces light pollution in cities, this positive side effect does not counterweight the concern about crime, personal security and traffic safety among local citizens.

There is no sharp objective threshold between acceptable and inadequate illuminance in cities. Perceived lack of safety depends on several lighting parameters, including the average illumination level, the spatial uniformity of illuminance, and the light color [4], but the local environment and personal factors also influence how much light is considered to be safe in an urban setting. The feeling of safety is the lowest in the dark and goes up with increasing illuminance reaching saturation at the upper end of twilight conditions. Beyond a relatively low level of 5–10 lux, shedding more light on the street results only in a minor increase in the feeling of safety [5].

More light on the road, however, gives rise to light pollution. High level of public lighting has a negative environmental impact affecting humans, animals, and plants alike [6]. Moreover, energy-efficient LED lighting with significant blue content raises health concerns attributed to circadian disruption [7]. Recent studies propose solutions to measure and mitigate the environmental impact of oversized lighting systems in the context of street lighting standards [8]. Urban planners must find a tradeoff between the conflicting objectives of reducing light pollution, cutting back on energy bills, and increasing the public perception of safety.

The same argument holds for traffic safety as well. The frequency of night accidents negatively correlates with road luminance [9]. However, there are other factors, like weather and road conditions which also have a pronounced effect on the probability of night collisions [10]. Conclusions of statistical analyses change as the weight of actual electricity price increases while assessing the tradeoff between adequate lighting and affordable electricity bill. Studies in the 1960s [11] and 1970s [12] argued for the importance of a higher level of illumination in public places in a period of abundant electricity at night, whereas today, at the time of growing stake of solar power in the energy mix and soaring electricity prices the balance tilts towards less light, less cost [13].

Instead of making arbitrary decisions on the illumination level of urban streets, municipalities can rely on the series of European road lighting standards EN 13201 [14] providing guidelines to adjust the lighting conditions to the actual traffic conditions. The luminance and illuminance recommendations are based on empirical investigations reflecting a cross-industry consensus [10]. According to the standard, each street of a city is associated with a lighting class. The lighting class is determined by several factors, including time-dependent parameters of traffic volume and traffic composition. The lighting design is carried out for the most demanding traffic conditions requiring the highest level of illuminance on the road surface. Since peak hours are usually in the mornings and in the afternoons, and traffic volume is low late at night, the standard enables the illuminance/luminance of the road to be reduced relative to the nominal level.

The traffic-regulated dynamic lighting is one of the smart city solutions [6] critical in achieving the sustainable development goals of the 2030 Agenda of the United Nations [15]. The two key elements of the control strategy are traffic monitoring and luminaire dimming. A great variety of traffic sensing technologies have been implemented in smart lighting systems: simple motion sensors [16], received signal strength (RSS) detection of radio waves [17], acoustic [18] and ultrasonic [19] sensors, and video cameras [20].

While simple sensors can be used for vehicle counting only, smart camera systems equipped with powerful object detection algorithms deliver detailed information about both the traffic volume and traffic composition [21]; therefore, computer vision is widely used in advanced adaptive lighting applications [22].

The energy saving resulting from the implementation of adaptive lighting is ultimately determined by the temporal profile of traffic volume. Energy cost reductions between 30–70% have been reported in real-life applications [23–25]. Despite its substantial operating cost-saving potential, full-fledged smart systems incorporating sensor networks and individually controlled luminaires are cost prohibitive for many municipalities. Although additional services of smart infrastructure, *e.g.,* remote monitoring and predictive maintenance, deliver more value for the street lighting operator, the complex IoT system is not affordable for small communities.

Timing is a more common and cost-effective control method of public lighting. On and off times as well as the dimming profile can be pre-programmed in luminaires or in segment controllers. Eliminating the sensors from the control loop results in reduced investment and operating costs, but the system will lose its capability to adapt to fluctuations in the daily traffic profiles [24].

Motion and light sensors may also be integrated into a lighting fixture establishing autonomous luminaire control. This approach is used mainly for pedestrian zones or bicycle roads [26]. The advantage is very high responsiveness and good energy-saving potential at a moderate increase in investment cost. The disadvantage is that on the same road section, there are continually evolving full power and dimmed or off states, and the fluctuating light level may be disturbing to the neighborhood [27].

Several publications deal with the energy saving resulting from traffic adaptive lighting control [23,28–30] in accordance with road lighting standards. Comparison of the previous (2004) and current versions of CEN/TR 13201-1:2014 highlighted major energy saving improvement from 27% to 47% in a case study of Krakow, Poland [23] attributed solely to the change in legislation. The luminous flux of street lighting luminaire is adjusted according to the traffic intensity detected by the sensors. The energy saving also depends on the sampling frequency and the averaging window size. Traffic intensity data are more often integrated over a time period exceeding the 1–2 min traffic light cycles, and dimming levels are updated every 15–60 min [23].

Energy consumption reduction at the level of 15% was attributed to dynamic control in another case study highlighting the advantage of the automated design process of street lighting systems [29]. Another suburban case study reported a 45% reduction in electricity consumption as a result of dynamically changing the street lighting classes during the day. An additional 15% energy saving would be possible if luminance criteria were converted to mesopic luminance values [30]. In this report, however, the authors used upfront assumptions about the evolution of lighting classes during the day and did not use real traffic data in their calculations.

The majority of publications in the field of smart street lighting have focused on the technology connecting lighting equipment with sensors and controllers. The energy-saving figures reported span over a wide range and are specific for a pilot installation. Municipalities would need a simple tool to collect traffic information and gather reliable local data to compare the energy consumption and environmental impact of various lighting control solutions.

Current high electricity prices unlock previously untapped energy-saving opportunities for municipalities. Decision makers ultimately have four options to choose from while considering lighting upgrade projects:

1. Invest in traffic sensor-controlled networked lighting solutions.
2. Establish a pre-programmed dimming schedule for street lighting.
3. Instigate a switch-off scheme during the night.
4. Maintain constant power operation between dusk and dawn.

The objective of this research was to develop a methodology comparing the energy-saving potential of the lighting control options and highlight the advantages and disadvantages of dynamic lighting relative to the scheduled switch-on and switch-off schemes. The same traffic data set was applied for the four scenarios. The case study was carried out on a road section of a Hungarian town, and traffic volume and composition data were gathered over one year.

2. Data Acquisition and Processing

The road section selected for this study is located in Gödöllő, Hungary, a town 25 km northeast of Budapest. On both edges of the two-lane, two-way street, bicycle lanes dedicate exclusive space for bicyclists. Sidewalks separated from the roadway by an unpaved buffer zone provide space for pedestrians. An IP camera with a resolution of 416 × 416 pixels was aimed at a parking lot providing images of a 25 m long road section as well. The resolution of the surveillance camera was sufficient for object detection, but personal information about the drivers or pedestrians was not possible to be identified. Images were not stored except for illustrations and documentation of the project.

2.1. Image Acquisition and Processing

Figure 1 shows an image of the night scene observed by the camera. The video signal was processed in quasi-real time by the YOLOv5 object detector [31]. The object identification algorithm was previously trained by the KITTI dataset [32] to identify cars, trucks, buses, motorcycles, bicycles and pedestrians. Moving objects were discriminated from the background and then classified into the above categories. The traffic counts related to each category were summed hourly and stored in a database.

Figure 1. The road section on the camera image at night. The object identified as a car is in the orange bounding box.

The traffic counting method was tested for consistency by comparing manually recorded observations with automatic machine vision data gathered at intense and low traffic conditions. Missed object identification due to overlapping images of inbound and outbound traffic was a rare event, with less than 0.5% occurrence observed only in high traffic. In some instances, vans were categorized as cars, not as trucks, but this incorrect classification did not change the total number of vehicles in the motorized traffic category used in the calculations. In our analysis, traffic data recorded between 16 July 2021 and 15 July 2022 were used. The database, composed of 8760 rows, has been cleaned prior to processing by identifying corrupted records. Missing and incorrect data were manually checked and replaced by interpolating neighboring values of the dataset. In the cleaned database, the traffic counts were aggregated into two higher categories: motorized and non-motorized traffic. This information was used to characterize the traffic composition.

2.2. Calculating Turn-On and Off Times

For each day of the year, the times of sunrise and sunset, as well as the beginning of civil dusk and end of civil dawn, were calculated using the Astra open source python module [33]. Under clear sky conditions at the boundaries of civil twilight, the ambient illuminance is about 3.4 lx, which is still below the threshold of dusk-to-dawn switches. During twilight, the Sun is under the horizon, and light scattered in the upper atmosphere illuminates the Earth's surface, often creating extreme visibility conditions for drivers [34]. Ambient illuminance changes rapidly with the solar elevation also influenced by weather conditions [35]. Depending on sky coverage, the exact time when street lights can be turned off vary between the start of dusk and the sunrise. Similarly, public lighting is switched on between sunset and the end of civil dusk. In order to maintain consistency with historical time control approaches we fitted the on and off times to the astronomical calendar [36] of public lighting still in use in many Hungarian towns.

We determined the value of the fitting parameter ($\boxed{k_{off}}$) in equation 1 by minimizing the sum of the least squares of the residuals [37] between the estimated off time ($\boxed{t_{off}}$) and the value in the astronomical calendar. The public lighting switch on time was calculated in a similar way according to equation 2. A detailed explanation of all symbols and abbreviations used in this paper is listed in Table S1.

$$t_{off} = t_{dawn} + k_{off} \cdot (t_{dawn} - t_{sunrize}), \quad (1)$$

$$t_{on} = t_{sunset} + k_{on} \cdot (t_{dusk} - t_{sunset}), \tag{2}$$

In Figure 2, the calculated switch on and off times are presented along with the astronomical calendar. The total time for the astronomical calendar was 3988 h. In the case of the fitted on and the off parameters the annual service time was 3992 h.

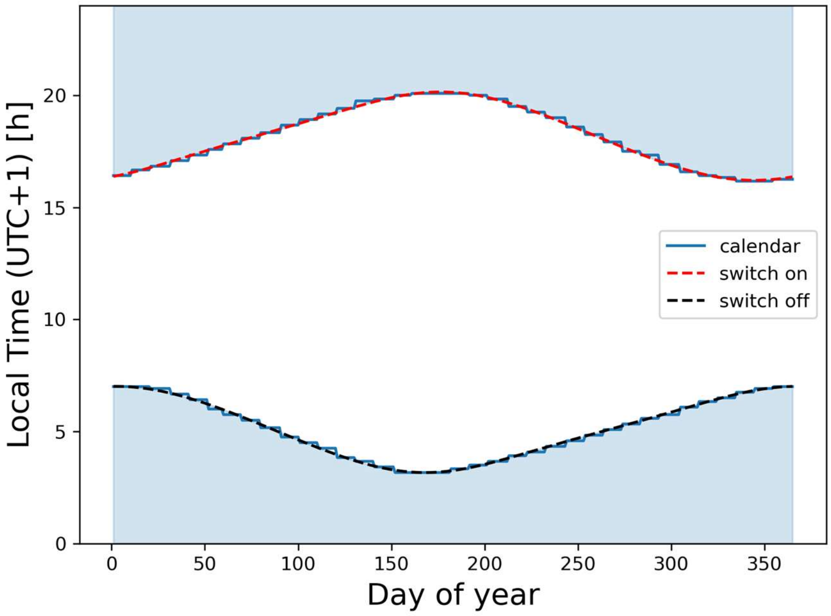


Figure 2. Calculated switch on (red) and off (black) times throughout the year. The blue step line represents the on and off times of the astronomical calendar.

2.3. Lighting Classes

The CEN/TR 13201-1:2014 Technical report [14] provides guidelines on selecting the lighting class of the road section. In our case study, the recommendations for M classes intended for the drivers of motorized vehicles apply. For the selection of the appropriate lighting class, several fixed and time-dependent road parameters are considered. For each parameter, a weighting factor is assigned. The sum of all weights (V_{WS}) subtracted from 6 yields the M lighting class specific to the actual road conditions. The average road luminance associated with the specific lighting class is determined in EN 13201-2: 2015 [14]. In Table 1, the traffic-dependent road parameters are listed along with the weighting values associated with six possible scenarios on the investigated road section. From the eight parameters listed in the standard, traffic volume and traffic composition were considered to be time-dependent factors, whereas the remaining six parameters were constant: design speed (−1), separation of carriageways (1), junction density (0), parked vehicles (1), ambient luminosity (0) and navigational task (0). The sum of the time-independent weighting factors is 1 for each case, as reflected by the third row in Table 1. Depending on the relative traffic volume defined as the quotient of the actual traffic volume and the road capacity, the weighting value can take three different values: 1 for relative traffic volume greater than 0.45; −1 for less than 0.15; and 0 if the relative traffic volume is between 0.15 and 0.45. The traffic composition is 0 in the case of motorized traffic only. For mixed, simultaneous motorized and non-motorized traffic, the weighting value is 1. Case 1 represents the most stringent conditions defined as the normal lighting class in the standard. The weighting value of the traffic volume is 1, corresponding to high traffic volume exceeding 45% of the total road capacity. The weighting value of 1 in the case of traffic composition corresponds to mixed traffic when both motorized and non-motorized traffic is present on the road. The lighting of the road should be designed to meet the average luminance requirement associated with the normal lighting class. In static lighting conditions, this average luminance is maintained throughout the night between dusk and dawn.

Table 1. Traffic-dependent parameters are used for the determination of the lighting class of the road section. Constant parameters include design speed (−1), separation of carriageways (1), junction density (0), parked vehicles (1), ambient luminosity (0) and navigational task (0).

Parameter (Weights)	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Traffic volume (−1,0,1)	1	0	1	−1	0	−1
Traffic composition (0,1)	1	1	0	1	0	0
Sum of constant parameters	1	1	1	1	1	1
V_{WS}	3	2	2	1	1	0
6-V_{WS}	3	4	4	5	5	6
Lighting class	M3	M4	M4	M5	M5	M6
Average luminance [cd/m^2]	1.00	0.75	0.75	0.50	0.5	0.3
Relative photon flux	100%	75%	75%	50%	50%	30%

Traffic volume and composition change with time, and so do the actual lighting class and luminance requirement of the street. The road lighting standard enables the road luminance to be adapted to the actual traffic conditions. In our study, Case 6 corresponds to the lowest traffic conditions, with traffic volume less than 15% of the road capacity corresponding to the weighting factor of −1. The zero weight for traffic composition corresponds to motorized traffic only.

2.4. Effective Service Time Calculations

As the traffic volume or composition changes, the lighting class of the road can be revised, and the road luminance can be adapted to the actual traffic conditions by reducing the power of the luminaires. For each and every hour of the period between 16 July 2021 and 15 July 2022, we calculated the relative traffic volume and determined the traffic composition. Using the selection rules described in Section 2.3, the relative photon flux of the luminaires was determined. We calculated the operation time of the lighting equipment (Δt_i) for each i hour of the day ($i = 0, 1, 2, \ldots 23$) and for each day of the year. In the daytime, when $t_{off} < t_i < t_{on}$ of the same day, $\Delta t_i = 0$. During the night, the operating time, $\Delta t_i = 1$. In the hour of dusk and dawn, the operating time is the fraction of the hour with a value between 0 and 1: $\Delta t_i = t_{off} - t_i$ at dawn and $\Delta t_i = t_i - t_{on}$ at dusk.

The energy saving at the luminaire level is the difference between the energy consumed at full power and at reduced power. The efficacy of the LED luminaires changes with the dimming value; therefore, a certain percentage reduction in luminous flux will result in slightly less reduction in electricity consumption. To exclude the luminaire-specific parameters from our discussion, we report the energy saving as a reduction of effective service time ($\Delta t_{eff,i}$) defined as the ratio of adapted (Φ_i) and normal (Φ_n) luminous flux multiplied by the operating time (Δt_i) of the street lighting. By adding up the effective service time in a day, the daily effective service time is calculated according to equation 3.

$$\Delta t_{eff} = \sum_{i=0}^{23} \Delta t_i \frac{\Phi_i}{\Phi_n} \tag{3}$$

The baseline in our calculation is always the static operation at constant nominal power between t_{on} and t_{off}. A luminaire operating at the nominal power for the time period of the effective service time produces the same amount of luminous energy (luminous flux × operating time) as the luminous energy generated by the adaptive lighting system during the operating period between t_{on} and t_{off}.

3. Results

Our investigation was restricted to analyzing traffic information in order to estimate the energy-saving potential of two different lighting control options. In the first approach, we assumed that the light output of the luminaires is controlled by the real-time signal of traffic sensors predicting the traffic volume in our data set. The luminous flux of the luminaires is updated every hour, so the lighting system does not respond to minute-scale traffic fluctuations. The relatively low responsiveness leads to slow transitions in road illuminance but also limits the energy-saving potential of the system.

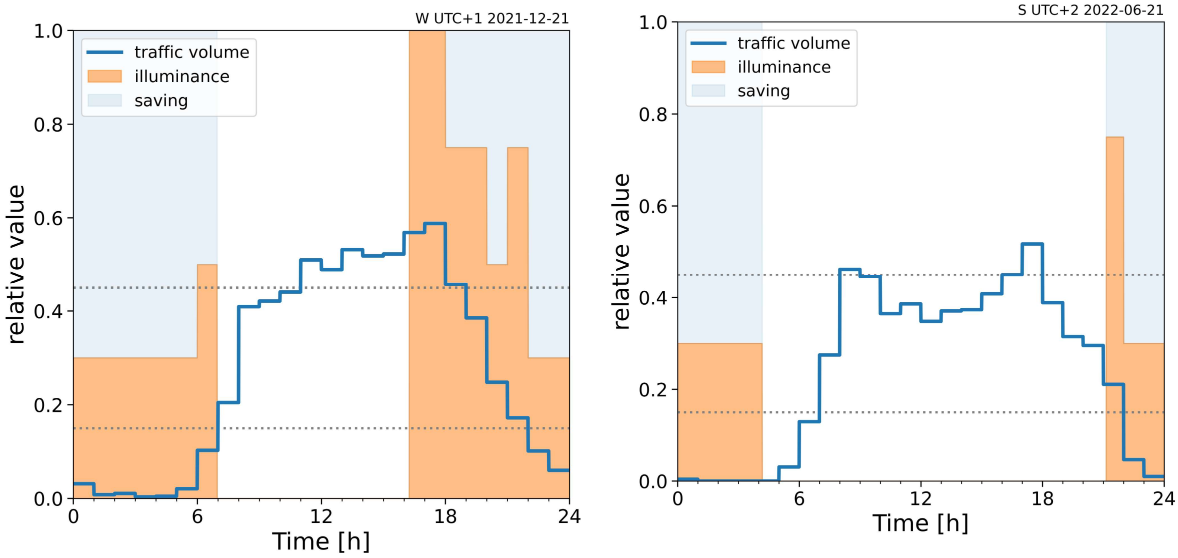
In the second approach, requiring a simple time controller only, the dimming schedule of the luminaires is pre-programmed, and the lighting control is established on a statistical basis. Knowing the traffic volume distribution characteristic for the day of the year, the road illuminance is set to be equal to or greater than the minimum requirement of the standard. In the next two sections, we present the estimated daily, monthly and yearly saving potential for a sensor-based dynamic lighting system followed by the statistical analysis of traffic data for the time-controlled scenario.

3.1. Sensor-based Adaptive Control

Relative traffic volume, relative illuminance levels and related savings are presented for the (a) shortest and (b) longest days of the year in Figure 3. Table 2 complements this information with traffic composition summarized for these two days. The blue step line in Figure 3 represents the temporal evolution of the relative traffic volume. The horizontal dotted lines show the 15% lower and 45% upper limit for the road class selection. Motorized traffic is dominant on this street; the ratio of pedestrians and bicycles is only a few percent of the total traffic volume. Since non-motorized traffic is absent late at night and the relative traffic volume is below 15%, the road conditions correspond to Case 6 of Table 1. The relative photon flux of the luminaires and the relative road illuminance is as low as 30% of the nominal value, as indicated by the yellow bars in Figure 3. At 5 am the traffic starts increasing, reaching a maximum in the afternoon followed by a gradual decrease until midnight. The afternoon peak hours fall in the dark period in wintertime; therefore, the street lighting is expected to operate at full power. With declining traffic volume road illuminance can be decreased, therefore the saving indicated by the height of blue areas is increasing.

Table 2. Daily traffic composition is measured on the summer and winter solstice.

Date	Car	Truck	Bus	Motorcycle	Bicycle	Pedestrian	Total
21 June 2022	8115	402	19	72	86	52	8746
	92.8%	4.6%	0.2%	0.8%	1.0%	0.6%	100%
21 December 2021	9838	235	52	9	30	52	10,216
	96.3%	2.3%	0.5%	0.1%	0.3%	0.5%	100%



(**a**) (**b**)

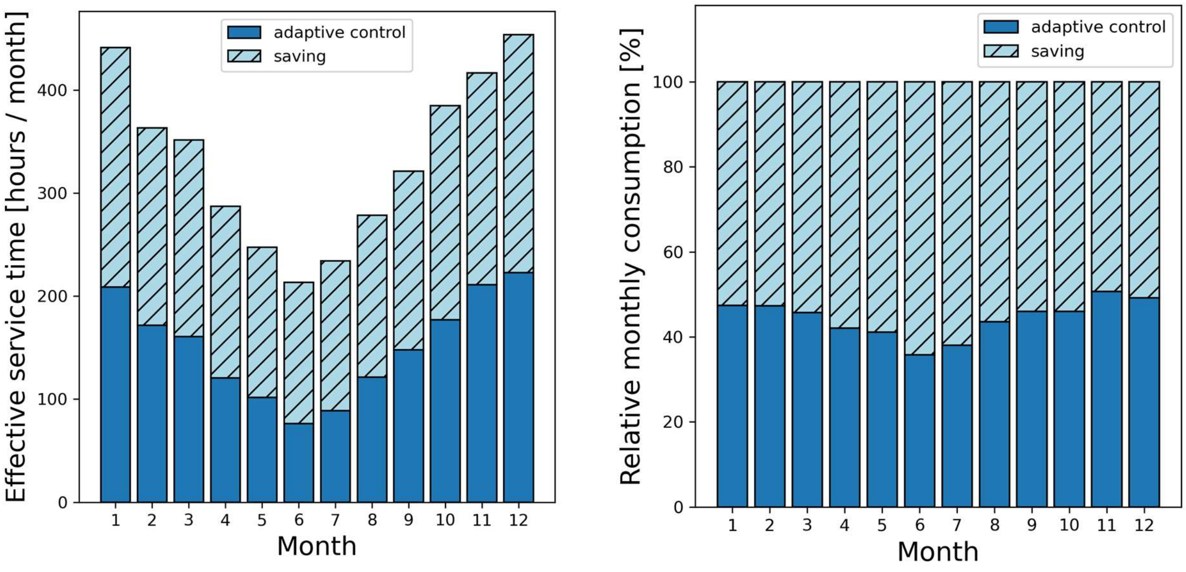
Figure 3. Relative traffic volume and calculated illuminance levels for the (**a**) winter and (**b**) summer solstice. The light blue shaded area represents the saving entitlement of the adaptive lighting.

The daily savings are summarized in Table 3. At the summer solstice, on 21 June, the operating time of the luminaires is only 7.03 h. Due to the reduction in the luminous output, a luminous energy saving of as high as 64.5% can be achieved. On 21 December, the operating time of the lighting system is 14.71 h and the effective service time was also much longer compared to the summer value. Since the peak hours overlap with the lighting period, the energy saving is reduced relative to summertime, but still, close to 50% effective service time reduction could have been realized on this date with adaptive street light control.

Table 3. The effective service time, the total operating time and the associated saving entitlement are calculated for the summer and winter solstice.

Date	Effective Service Time [h]	Operating Time [h]	Saving Entitlement
21 June 2022	2.50	7.03	64.5%
21 December2021	7.38	14.71	49.8%

The seasonal trend is visualized in Figure 4. The absolute value of the monthly effective service time is depicted in Figure 4a, while the proportion of the consumption and saving is shown in Figure 4b. With adaptive control, the highest monthly consumption is in December, with 223 h effective service time. When lighting is operated at full power between dusk and dawn the total service time amounts to 454 h, consequently the saving resulting from traffic sensor-controlled dynamic lighting is 231 h which is 50.9 % of the total consumption. During the transition from winter to June, the absolute value of the effective service time, saving and total consumption decreases, reaching the minimum at 88.9 h, 145 h, and 234 h, respectively. The relative saving grows to the 62% monthly maximum in June because lights are off at the start of morning traffic and switched on at moderate power late in the evening when afternoon traffic has already decayed.



(**a**) (**b**)

Figure 4. Effective service time of the street lighting as a function of the month of the year. (**a**) Total effective service time in hours; (**b**) The effective service time normalized to the total dark time period of the month. The hashed columns represent the savings resulting from adaptive control.

3.2. The Effect of Seasonal Time Change

We considered three scenarios regarding the time zone selection when aggregating effective service time data to the monthly intervals. Currently, the seasonal time change is in effect in most European countries. In the winter time, Hungary uses UTC +1 time. UTC stands for Coordinated Universal Time (UTC). UTC +1 indicates the one-hour time offset relative to the primary time standard [38]. Daylight saving time starts on the last Sunday of March when clocks are advanced by one hour, pushing Hungary into the UTC +2 time zone. Since there is a pending directive of the European Parliament and of the Council on discontinuing seasonal changes of time and leaves on the member states which time zone they would maintain [39], we calculated annual effective service time and related savings for all the three options: seasonal time change from UTC +1 to UTC +2 on 27 March 2022 and time change from UTC +2 to UTC +1 on 31 October 2021; as well as UTC +1 or UTC +2 for the entire year.

Calculated effective service time data are summarized in Table 4. The annual baseline for saving calculation is the 3992 h service time of the streetlight controlled by the astronomical timer. The calculated effective service time is only 1807 h for the actual summertime arrangement resulting in 54.7% luminous energy saving. Time zone selection has a minor effect on top of the introduction of adaptive control: savings can be further increased by staying with the summer time (UTC +2) all around the year, whereas UTC +1 would result in a few percent fewer savings. Our key assumption was that the time profile of the traffic volume is independent of the time zone selection and did not contemplate how the prolonged darkness with UTC +2 would affect drivers' habits during wintertime.

Table 4. The annual effective service time, saving entitlement for the lighting control modes, as well as the number of over and under-illuminated hours calculated from the data set.

Control Mode	Time Zone	Effective Service Time [hours/year]	Saving Entitlement	Over-Illuminated Hours in a Year	Under-Illuminated Hours in a Year
Sensor based adaptive control	UTC + 1	1910	52%	0	0
	UTC + 1 / UTC + 2	1807	55%	0	0
	UTC + 2	1748	56%	0	0
Pre-programmed timer	UTC + 1	2307	42%	1588 (40%)	170 (4.3%)
	UTC + 1 / UTC + 2	2205	45%	1610 (40%)	181 (4.5%)
	UTC + 2	2167	46%	1684 (42%)	182 (4.6%)
3 h per night switch-off	UTC + 1 / UTC + 2	2897	27%	2711 (68%)	1095 (27%)
Dusk to dawn astronomical timer	UTC + 1 / UTC + 2	3992	0%	3806 (95%)	0

3.3. Pre-programmed Lighting Schedule

Every single day is different, and the temporal evolution of traffic volume does not repeat itself, but there are still some periodic patterns that can be revealed by data analysis. Figure 5 depicts individual traffic volume data grouped by the hours of the day. All records of the one-year period are shown except interpolated data which were excluded from the statistical analysis. Horizontal lines representing Sundays dominate the lower end, whereas workdays tend to be on the top of the distributions.

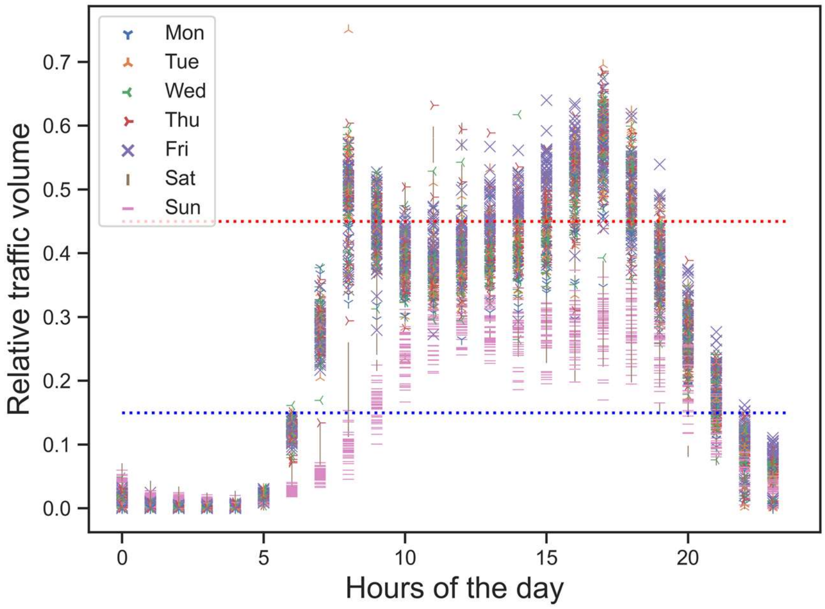


Figure 5. Relative traffic volume data for the one-year period grouped by the hour of the day. The horizontal dotted lines indicate the lower (blue) and upper (red) traffic volume limits used for lighting class selection.

Relative traffic volume remained below the 0.15 threshold on each night of the year, but fluctuations are rather high during the day. The weekly profile shown in Figure 6 highlights the difference between workdays and weekends. On the week of 4 October 2021, traffic volume follows a similar pattern from Monday to Friday. The height of the traffic volume peak is lower on Saturday and the lowest on Sunday. Extra holidays modify this weekly pattern: traffic on national holidays, Easter and Whit Monday, during the Christmas holiday traffic flow was closer to Sunday traffic than for the day of the week; therefore, all non-workdays were reclassified as Sunday-like days in our analysis. The distribution of traffic volume for each day of the week and each hour of the day were determined and compared to the 15% and 45% traffic volume limits used for road class selection.

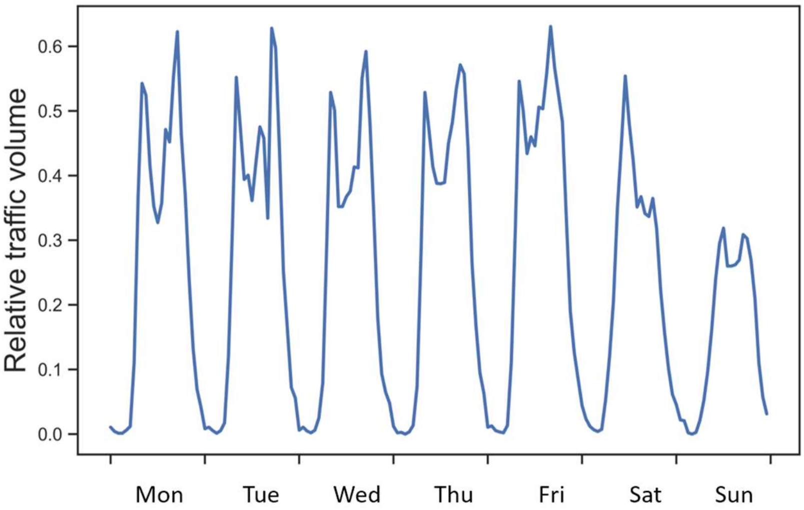


Figure 6. Relative traffic volume between Monday, 4 October and Sunday, 10 October 2021.

As an example of the early morning scenario, the boxplot in Figure 7 shows the traffic volume distributions as a function of the day of the week for 6 am. The box extends from the first quartile (Q1) to the third quartile (Q3) of the data with a line at the median. The whiskers extend from Q1 − 1.5 × IQR to Q3 + 1.5 × IQR. The inter-quartile range, IQR, is defined by IQR = Q3 − Q1. The markers denote the outliers from the distributions. This analysis has been completed for each and every hour of the day. The pattern of workdays and holidays was significantly different from each other. Therefore we determined two sets of traffic volume weighting values for the road class selection.

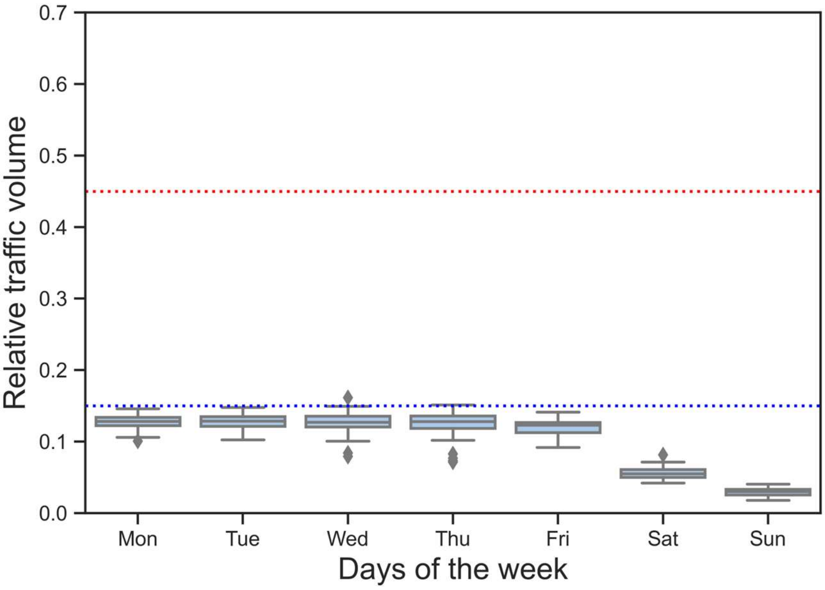


Figure 7. Relative traffic volume distributions at 6 am grouped by the day of the week. Red and blue dotted lines represent the 45% upper and 15% lower limits for the road class selection.

Our objective was to minimize the number of cases where the illuminance level is lower than the standard recommendation. Although the vast majority of workday data points were below the 15% threshold, in our calculation, we assigned the medium level, 0 traffic volume weighting value to all 6 am data points ranging from Monday to Friday. The weighting value of −1 was attributed to Saturdays and Sundays at 6 am.

A similar analysis is shown for 6 pm data in Figure 8. From Monday to Friday majority of data points were above the 0.45 threshold. Therefore all 6 pm data points were given the highest +1 weighting value, whereas Saturdays and Sundays got 0. We did not make a difference in traffic composition between the days. From 1 am to 4 am, each hour was considered to have motorized traffic only with a weighting factor of 0, whereas the rest of the hours were regarded as mixed traffic with a weighting value of 1. Using the road class selection rules, the relative irradiance levels were calculated for workdays and holidays.

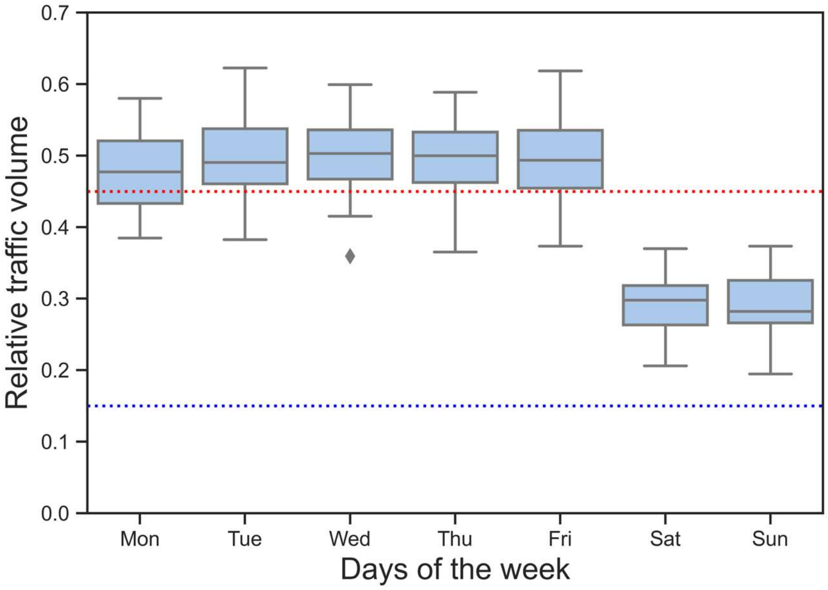


Figure 8. Relative traffic volume distributions at 6 pm grouped by the day of the week. Red and blue dotted lines represent the 45% upper and 15% lower limits for the road class selection.

Figure 9 shows the dimming schedule as a function of the hours of the day, both for workdays and holidays. The two schedules are identical between 6 pm to 5 am, and only the lack of Saturday and Sunday traffic peaks drive the difference between the two curves. The relative illuminance (photon flux) schedule can be the basis of time-controlled street lighting.

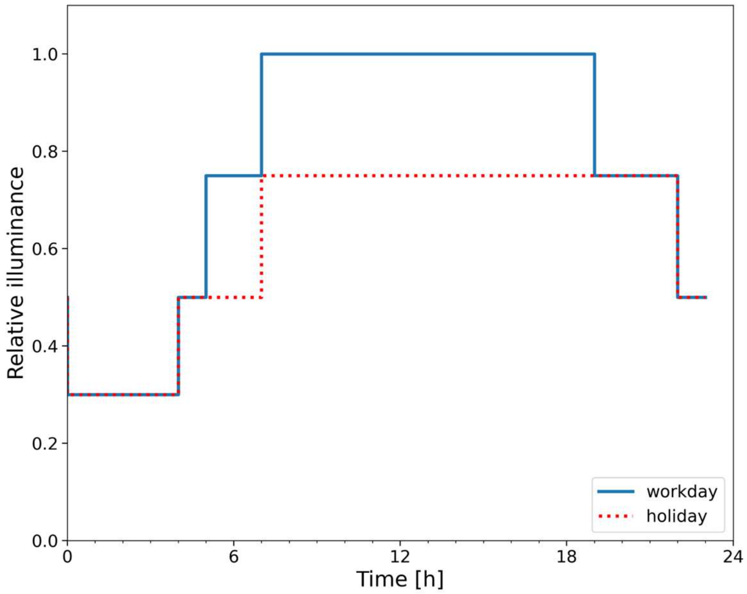


Figure 9. Relative illuminance levels for pre-programmed daily schedule calculated for workdays and holidays.

Table 4 contains the annual effective service times and associated savings calculated for all three-time zone variations. The simple time control results in higher illuminance than required by the standard in several cases; therefore, the savings realized are lower than that of real-time control. Nevertheless, savings are still significant and exceed the amount of energy savings municipalities can realize by completely switching off streetlights.

4. Discussion

The traffic sensor-based control dynamically adapts lighting power to the actual traffic conditions. All other control modes deviate from the adaptive case by over or under-illuminating the street relative to the standard's recommendations. Table 4 lists the duration of over and under-illuminations which can be interpreted as false-positive and false-negative errors of the control modes. The dusk to dawn controller substantially over-illuminates the streets by shedding more light than required in 95% of the total 3992 service hours. From another perspective, the total installed power is fully utilized in 5% of the total service time, only providing significant energy-saving opportunities for the control modes.

The 3 h per night switch-off amounts to 1095 dark hours in a year corresponding to 27% of the total service time. The scheduled 3 h switch-off reduced the number of over-illuminated hours relative to the constant power mode. Despite the energy saving, luminaires operated at higher than the required power for 2711 h in a year corresponding to 68% of the service time. The pre-programmed timer option proved to be much more energy efficient than the 3 h per night switch-off. Due to the relatively stable time profile of the traffic volume, energy saving was as high as 45% in the case of the seasonal time change, whereas the ratio of under-illumination was 4.5% only.

In Table 4, we did not show the extent of under or over-illuminations which can be a significant weighting factor while considering the environmental impact of the lighting mode. In the case of scheduled switch-offs, over- and under-illumination correspond to the maximum and zero levels, respectively, whereas in the case of pre-programmed dimming, the deviation is typically limited to one step above or below the illuminance required by the actual traffic conditions.

The normal lighting class of the road section in our study was M3. The energy requirements of street lighting can be cut in half because the street can be downgraded to lower lighting classes at low traffic conditions. There is less room for luminance reduction on M4 and M5 roads. Since M6 class corresponds to the lowest requirements in EN 13201, the luminance of an M6 road is expected to be traffic independent.

In our case study, traffic volume profiles exhibited regular periodic patterns for weekdays and holidays, enabling the application of a pre-programmed dimming schedule. The investment cost of time-controlled street lighting with a 45% energy-saving option can be much more attractive for municipalities than the financial burden of a full-fledged network solution offering an additional 10% energy cost reduction. We did not consider specific technical products, and the economic assessment is beyond the scope of this paper. Our objective was to present a methodology for the estimation of the energy-saving potential of street lighting solutions, which can feed a complete life cycle analysis [40,41] to provide a full picture of the economic and environmental impact of the traffic-regulated lighting control systems.

The luminance and illuminance levels of the lighting classes as well as the 15% and 45% traffic volume limits, reflect the industry consensus established prior to the current energy crisis. Shutting down street lighting in cities can be accepted as a temporary emergency measure, but the 60+ years of lighting research cannot justify street darkening as a long-term sustainable solution.

5. Conclusions

With this case study, we demonstrated that adaptive street lighting could be a viable alternative to turning off public lighting at night. Implementation of dynamic light control results in significant electricity savings without harm to road safety and public security. The largest saving, 55%, can be achieved with a responsive sensor network. Pre-programmed dimming schedule based on long-term traffic data analysis delivered 45% whereas 3 h per night complete switch off resulted in only 25% savings relative to the constant full power operation between dusk and dawn. The 3 h shutdown is the most contradictory scenario leaving streets in complete darkness at 27% and over-illuminated in 68% of the total service hours.

Further research and industry-wide discussion are required to fine-tune the limits in the standard and accommodate advanced and affordable traffic adaptive solutions allowing a reduction in energy consumption and light pollution while ensuring traffic safety and personal security in urban streets.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Table S1: Nomenclature.

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References

1. Energy Price Rise Since 2021. Available online: https://www.consilium.europa.eu/en/infographics/energy-prices-2021/ (accessed on 18 January 2023).
2. Ewen, M. European Wholesale Electricity Price Data. Available online: https://ember-climate.org/data-catalogue/european-wholesale-electricity-price-data/ (accessed on 25 January 2023).

3. Zimmermann, A. Europe's Streets Go Dark to Save Energy. Available online: https://www.politico.eu/article/europe-cities-streets-dark-lights-off-save-energy/ (accessed on 25 January 2023).
4. Peña-García, A.; Hurtado, A.; Aguilar-Luzón, M.C. Impact of Public Lighting on Pedestrians' Perception of Safety and Well-Being. *Saf. Sci.* **2015**, *78*, 142–148. https://doi.org/10.1016/j.ssci.2015.04.009.
5. Svechkina, A.; Trop, T.; Portnov, B.A. How Much Lighting Is Required to Feel Safe When Walking Through the Streets at Night? *Sustainability* **2020**, *12*, 3133. https://doi.org/10.3390/su12083133.
6. Tavares, P.; Ingi, D.; Araújo, L.; Pinho, P.; Bhusal, P. Reviewing the Role of Outdoor Lighting in Achieving Sustainable Development Goals. *Sustainability* **2021**, *13*, 12657. https://doi.org/10.3390/su132212657.
7. Dolsen, E.A.; Wyatt, J.K.; Harvey, A.G. Sleep, Circadian Rhythms, and Risk Across Health Domains in Adolescents with an Evening Circadian Preference. *J. Clin. Child Adolesc. Psychol.* **2019**, *48*, 480–490. https://doi.org/10.1080/15374416.2017.1416620.
8. Gălăţanu, C.D.; Canale, L.; Lucache, D.D.; Zissis, G. Reduction in Light Pollution by Measurements According to EN 13201 Standard. In Proceedings of the 2018 International Conference and Exposition on Electrical And Power Engineering (EPE), Iasi, Romania, 18–19 October 2018; pp. 1074–1079.
9. Jackett, M.; Frith, W. Quantifying the Impact of Road Lighting on Road Safety—A New Zealand Study. *IATSS Res.* **2013**, *36*, 139–145. https://doi.org/10.1016/j.iatssr.2012.09.001.
10. Fotios, S.; Gibbons, R. Road Lighting Research for Drivers and Pedestrians: The Basis of Luminance and Illuminance Recommendations. *Light. Res. Technol.* **2018**, *50*, 154–186.
11. Sielski, M.C. Relationship of Roadway Lighting and Traffic Accidents. *Highw. Res. Board Spec. Rep.* **1965**, *93*, 172–177.
12. Janoff, M.S.; McCunney, W. Economic Analysis of Roadway Lighting. *J. Illum. Eng. Soc.* **1979**, *8*, 244–249. https://doi.org/10.1080/00994480.1979.10747870.
13. Steinbach, R.; Perkins, C.; Tompson, L.; Johnson, S.; Armstrong, B.; Green, J.; Grundy, C.; Wilkinson, P.; Edwards, P. The Effect of Reduced Street Lighting on Road Casualties and Crime in England and Wales: Controlled Interrupted Time Series Analysis. *J. Epidemiol Community Health* **2015**, *69*, 1118–1124.
14. CEN-CENELEC EN 13201 Standards for Road Lighting All Parts. Available online: https://www.en-standard.eu/csn-en-13201-1-4-road-lighting/ (accessed on 25 January 2023).
15. Transforming Our World: The 2030 Agenda for Sustainable Development | Department of Economic and Social Affairs. Available online: https://sdgs.un.org/2030agenda (accessed on 26 January 2023).
16. Sánchez Sutil, F.; Cano-Ortega, A. Smart Public Lighting Control and Measurement System Using LoRa Network. *Electronics* **2020**, *9*, 124. https://doi.org/10.3390/electronics9010124.
17. Jiang, Y.; Shuai, Y.; He, X.; Wen, X.; Lou, L. An Energy-Efficient Street Lighting Approach Based on Traffic Parameters Measured by Wireless Sensing Technology. *IEEE Sens. J.* **2021**, *21*, 19134–19143. https://doi.org/10.1109/JSEN.2021.3089208.
18. Barbagli, B.; Bencini, L.; Magrini, I.; Manes, G.; Manes, A. A Traffic Monitoring and Queue Detection System Based on an Acoustic Sensor Network. *Int. J. Adv. Netw. Serv.* **2011**, *4* , 27-37.
19. Kusum, T.; Islam, H.; Khatun, M. Ultrasonic Sensor Based Efficient and Energy Saving Street Lighting System. In Proceedings of the 2020 IEEE Region 10 Symposium (TENSYMP), Dhaka, Bangladesh, 5–7 June 2020; pp. 1321–1324.
20. Pi, Y.; Duffield, N.; Behzadan, A.; Lomax, T. *Computer Vision and Multi-Object Tracking for Traffic Measurement from Campus Monitoring Cameras*; American Society of Civil Engineers: Reston, VA, USA, 2022; pp. 950-958.
21. Gagliardi, G.; Lupia, M.; Cario, G.; Tedesco, F.; Cicchello Gaccio, F.; Lo Scudo, F.; Casavola, A. Advanced Adaptive Street Lighting Systems for Smart Cities. *Smart Cities* **2020**, *3*, 1495–1512.
22. Asif, M.; Shams, S.; Hussain, S.; Bhatti, J.A.; Rashid, M.; Zeeshan-ul-Haque, M. Adaptive Control of Streetlights Using Deep Learning for the Optimization of Energy Consumption during Late Hours. *Energies* **2022**, *15*, 6337. https://doi.org/10.3390/en15176337.
23. Wojnicki, I.; Kotulski, L. Empirical Study of How Traffic Intensity Detector Parameters Influence Dynamic Street Lighting Energy Consumption: A Case Study in Krakow, Poland. *Sustainability* **2018**, *10*, 1221. https://doi.org/10.3390/su10041221.
24. Marino, F.; Leccese, F.; Pizzuti, S. Adaptive Street Lighting Predictive Control. *Energy Procedia* **2017**, *111*, 790–799. https://doi.org/10.1016/j.egypro.2017.03.241.
25. Beccali, M.; Bonomolo, M.; Lo Brano, V.; Ciulla, G.; Di Dio, V.; Massaro, F.; Favuzza, S. Energy Saving and User Satisfaction for a New Advanced Public Lighting System. *Energy Convers. Manag.* **2019**, *195*, 943–957. https://doi.org/10.1016/j.enconman.2019.05.070.
26. Juntunen, E.; Tetri, E.; Tapaninen, O.; Yrjänä, S.; Kondratyev, V.; Sitomaniemi, A.; Siirtola, H.; Sarjanoja, E.-M.; Aikio, J.; Heikkinen, V. A Smart LED Luminaire for Energy Savings in Pedestrian Road Lighting. *Light. Res. Technol.* **2015**, *47*, 103–115.
27. Kovács, A.; Bátai, R.; Csáji, B.C.; Dudás, P.; Háy, B.; Pedone, G.; Révész, T.; Váncza, J. Intelligent Control for Energy-Positive Street Lighting. *Energy* **2016**, *114*, 40–51. https://doi.org/10.1016/j.energy.2016.07.156.
28. Wojnicki, I.; Komnata, K.; Kotulski, L. Comparative Study of Road Lighting Efficiency in the Context of CEN/TR 13201 2004 and 2014 Lighting Standards and Dynamic Control. *Energies* **2019**, *12*, 1524. https://doi.org/10.3390/en12081524.
29. Sędziwy, A.; Kotulski, L. Towards Highly Energy-Efficient Roadway Lighting. *Energies* **2016**, *9*, 263. https://doi.org/10.3390/en9040263.
30. Fryc, I.; Czyżewski, D.; Fan, J.; Gălăţanu, C.D. The Drive towards Optimization of Road Lighting Energy Consumption Based on Mesopic Vision—A Suburban Street Case Study. *Energies* **2021**, *14*, 1175. https://doi.org/10.3390/en14041175.
31. Jocher, G. YOLOv5 by Ultralytics. Available online: https://github.com/ultralytics/yolov5 (accessed on 19 January 2023).

32. Liao, Y.; Xie, J.; Geiger, A. {KITTI}-360: A Novel Dataset and Benchmarks for Urban Scene Understanding in 2D and 3D. Available online: https://www.cvlibs.net/datasets/kitti-360/index.php (accessed on 19 January 2023).
33. Kennedy, S. Astral. Available online: https://github.com/sffjunkie/astral (accessed on 19 January 2023).
34. Spitschan, M.; Aguirre, G.K.; Brainard, D.H.; Sweeney, A.M. Variation of Outdoor Illumination as a Function of Solar Elevation and Light Pollution. *Sci. Rep.* **2016**, *6*, 26756. https://doi.org/10.1038/srep26756.
35. MacInnis, D.D.; Williamson, P.B.; Nielsen, G.P. Sun Position and Twilight Times for Driver Visibility Assessment. *SAE Trans.* **1995**, *104*, 759–783.
36. Hungarian Standard MSZ 20194-2000: Artificial Lighting for Public Roads. Definitions, Principles. Available online: https://ugyintezes.mszt.hu/webaruhaz/szabvany-adatok?standard=100122 (accessed on 19 January 2023).
37. Kiemele, M.J.; Schmidt, S.R.; Berdine, R.J. *Basic Statistics–Tools for Continuous Improvement*, 4th ed.; Air Academy Press, Colorado Springs, CO, USA, 1997; ISBN 1-880156-06-7.
38. *ISO 8601-1:2019*; Date and Time—Representations for Information Interchange—Part 1: Basic Rules. Available online: https://www.iso.org/obp/ui/#iso:std:iso:8601:-1:ed-1:v1:en (accessed on 4 April 2023).
39. Ulvskog, M. REPORT on the Proposal for a Directive of the European Parliament and of the Council Discontinuing Seasonal Changes of Time and Repealing Directive 2000/84/EC | A8-0169/2019 | European Parliament. Available online: https://www.europarl.europa.eu/doceo/document/A-8-2019-0169_EN.html (accessed on 18 January 2023).
40. Bertin, K.; Canale, L.; Ben Abdellah, O.; Méquignon, M.-A.; Zissis, G. Life Cycle Assessment of Lighting Systems and Light Loss Factor: A Case Study for Indoor Workplaces in France. *Electronics* **2019**, *8*, 1278. https://doi.org/10.3390/electronics8111278.
41. Bertin, K. Analyse Des Impacts Environnementaux et Socio-Économiques Des Systèmes d'éclairage. Ph.D. Thesis, Université Paul Sabatier-Toulouse III: Toulouse, France, These de doctorat, Toulouse 3, 2022.