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Video-Based Analysis of a Smart Lighting Warning System for Pedestrian Safety at Crosswalks

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Highlights:

What are the main findings?

- The presence of an integrated lighting warning system near crosswalks significantly increases yielding compliance and allows drivers to respect the stopping distance before a pedestrian crossing.
- Five-month continuous monitoring of different warning lighting systems proved that the combination of lighting with in-curb fixed LED strips, orange flashing beacons, and dedicated LED lighting reduces drivers' speed compared to standard street lighting systems.

What are the implications of the main findings?

- Smart lighting systems detecting pedestrians at night, both in urban and suburban areas, are a valid solution to increase safety near pedestrian crossings. These smart systems improve drivers' vision and significantly reduce the risk of accidents between vehicles and pedestrians.
- In-curb fixed LED strips and flashing beacons increase driver attention towards pedestrians, thus making drivers stop vehicles at crosswalks, yielding to pedestrians.

Abstract: This study analyses five months of continuous monitoring of different lighting warning systems at a pedestrian crosswalk through video surveillance cameras during nighttime. Three different light signalling systems were installed near a pedestrian crossing to improve the visibility and safety of vulnerable road users: in-curb LED strips, orange flashing beacons, and asymmetric enhanced LED lighting. Seven different lighting configurations of the three systems were studied and compared with standard street lighting. The speed of vehicles for each pedestrian–driver interaction was also evaluated. This was then compared to the speed that vehicles should maintain in order to stop in time and allow pedestrians to cross the road safely. In all of the conditions studied, speeds were lower than those maintained in the five-month presence of standard street lighting (42.96 km/h). The results show that in conditions with dedicated flashing LED lighting, in-curb LED strips, and orange flashing beacons, most drivers (72%) drove at a speed that allowed the vehicle to stop safely compared to standard street lighting (10%). In addition, with this lighting configuration, the majority of vehicles (85%) stopped at pedestrian crossings, while in standard street lighting conditions only 26% of the users stopped to give way to pedestrians.

Keywords: pedestrian crosswalk; pedestrian safety; nighttime road safety; driver–pedestrian interaction; LED road lighting; road safety measures; lighting warning system

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1. Introduction

In the European Union, pedestrians are involved in one out of five fatal road accidents. In 2019, 72% of fatal crashes occurred in urban areas and 20% involved pedestrians, reaching 4628 deaths [1]. This figure is considerably high when considering other vulnerable road users, such as motorcyclists, amounting to 16%, cyclists, to 9%, and mopeds, to 3%. In

Italy, the number of road victims in 2021 amounted to 471 pedestrians, with a 15% increase compared to 2020 [2]. The number of fatal road accidents increased further in 2022, while remaining below pre-COVID-19 levels [3]. Data show that since 2009 almost 90% of the increase in pedestrian casualties occurred at night [4,5], probably due to high vehicle speeds. High speed is one of the main causes of road accidents involving pedestrians, especially at night in the dark. In addition, late braking, left turns on two-lane roads, pedestrian crossings, lighting poles reducing road visibility, and unprotected pedestrian areas should be mentioned. Pedestrian safety research has long recognised that darkness is a major risk factor in road crashes involving pedestrians [6–8]. Night collisions are usually more severe than day crashes since lighting conditions have an important impact on pedestrian safety. Literature and research in the field provide clear evidence of this. Schneider (2020) [9] showed that the death rate of pedestrians in dark conditions has increased steadily since the late 1970s. Since the early 1980s, the death rate has risen from about 63% to 76% in 2018 [5]. The highest risk of death for pedestrians is between 3 a.m. and 6 a.m. [10]. Night crashes at intersections have an 83% risk of being fatal in the absence of street lighting, while falling to 54% with street lighting [11]. Studies focused on how darkness affects drivers' vision, determining driving speed and the ability to detect an obstacle, thus estimating the correct stopping distance [12,13]. Sullivan and Flannagan (2001) [14] identified high speed at night as a high-risk factor for pedestrians, compounded by excessive alcohol use, both by pedestrians and motorists.

Several studies also showed that the retroreflection of road signs, correct lighting, and bio-movement significantly increase the distance from which a driver can detect a pedestrian [15]. Other studies proved that age or any visual impairment can negatively affect the ability of drivers to distinguish pedestrians at night [16]. The increase in fatal accidents at night is also closely linked to the type of infrastructure. Unsigned pedestrian crossings increase fatalities by 80.8%; 40–45 mph roads are often responsible for 54.6% of serious accidents, five-lane roads for 40.7%, urban streets for 99,7%, and high-flow roads for 81.1% [17]. Extending the curb could be the first infrastructure solution to the problem. Bella and Silvestri (2015) [18] found that a curb extension leads drivers to maintain the most appropriate speed when approaching a pedestrian crossing. More than 80% of drivers perceived curb extensions as effective and showed a greater willingness to yield to pedestrians, since the pedestrian crossing was better visible.

Speed, age, and type of infrastructure may affect drivers' vision, but it is definitely better in light conditions. The first big difference in terms of visibility on the road is between day and night [19,20]. Alogaili and Mannering (2022) [21] showed that nighttime crashes have more severe consequences for pedestrians over time. Technologies that seek to reproduce conditions of daytime visibility even at night (improved lighting, infrared pedestrian detection, etc.) may bring significant safety benefits, even if the increase in vehicle speed plays an important role in causing accidents. High speed reduces the overall ability of a driver to see and perceive [22] because they tend to focus on the centre of the road rather than the sides, from which pedestrians usually come [23]. At night, drivers do not moderate their speed to compensate for reduced visibility, while pedestrians overestimate the ability of drivers to see them [24]. In addition, the extensive use of mobile phones and other distracting devices can cause further safety problems for both drivers and pedestrians [25,26]. Proper street lighting lowers the risk of fatal crashes for pedestrians [27,28], while mitigating road crashes under different driving conditions [29]. Focusing on pedestrian crossings, several countermeasures could be taken to increase visibility so that drivers can stop in time and yield to pedestrians.

Hakkert et al. (2002) [30] added in-curb flashing lights near a pedestrian crossing. The average speed of vehicles approaching the area decreased by 2 to 5 km/h, while the number of drivers giving priority to pedestrians increased accordingly. This resulted in a significant reduction in vehicle–pedestrian crashes, as well as in the number of pedestrians crossing outside the marked pedestrian zone. Hussain et al. (2023) [31] showed that both LED light and advanced variable message signal (VMS) were useful in increasing visibility by up to

98.4% and reducing vehicle–pedestrian conflicts. Both devices were effective in motivating drivers to reduce vehicle speed in advance. Vignali et al. (2019) [32] studied the inclusion of flashing beacons near unmarked pedestrian crossings. They showed that flashing beacons increased fixations of "Yield here to pedestrian" vertical signs and improved the distance at which drivers could detect the presence of a pedestrian crossing the road. Hoye and Laureshyn (2019) [33] added the "SeeMe" light with automatic pedestrian detection to pedestrian crossing signs in residential areas. This lighting system on two-lane roads improved driver performance in areas with moderate motor vehicle volumes and speed limits of up to 50 km per hour. Shurbutt et al. (2009) [34] installed a rectangular side-mounted stutter-flash LED beacon system near a pedestrian crossing to increase the safe braking performance of vehicles toward pedestrians. Results showed a considerable increase in safety distances for a two-beacon system. Patella et al. (2020) [35] added white LED strips to evaluate drivers' speed at night. Results showed that the average travel speed was reduced by about 7.8 km/h. Studies reported that rectangular rapid flash beacons (RRFBs) installed at crosswalks improved drivers' braking performance and yielding rates at midblock crosswalks [36,37]. Goswamy et al. (2023) [38] demonstrated how rectangular rapid flashing beacons (RRFBs) reduce the severity of night crashes. Fitzpatrick and Park (2021) [28] showed that there were no substantial differences between daytime and nighttime driver-yielding performance with pedestrian hybrid beacons (PHBs), while rectangular rapid flashing beacons (RRFBs) were more effective at night.

Different light signalling systems have been extensively studied in the literature. However, few studies have analysed which configuration is the most effective for increasing the safety of weak road users at night near a pedestrian crossing. This study aims to assess the impact of integrated light warning systems on driver behaviour to identify the most effective configuration and increase the safety of vulnerable road users. The systems included a dedicated lighting vertical sign on both sides, side-mounted flashing beacons and in-curb LED strips for both warning and lighting pedestrian crossings. Seven different lighting configurations were studied and compared to current standard street lighting. Cameras installed near the pedestrian crossing monitored different lighting configurations continuously for five months. Compared to previous studies [39], continuous analysis of the lighting systems allowed users to be monitored without being aware of the experiment. The results obtained are evidence of the reliability of the integrated light warning system.

2. Materials and Methods

2.1. Pedestrian Crossing Lighting System

The pedestrian crossing chosen for the experimental system is located in Via Andrea Costa, in the Porto-Saragozza district of Bologna, Italy. This two-way road conveys the vehicles in the direction of the city avenues, and allows the flow both towards Bologna city centre and in the opposite direction, towards the nearest suburbs. In its current dual-strip configuration, the pedestrian crossing serves both pedestrians coming from and those heading to bus stops through the pedestrian safety island, as well as users swapping between the two existing pavements (Figure 1).

For the analysis of pedestrian crossings, a lighting system was introduced (Figure 2) consisting of the following:

- Movement sensor for the detection of pedestrians near the curb-side area.
- In-curb LED strips: Flexible in-curb LED strips of the Flexi-led line type, and adaptable to the desired shape, installed at both ends of the curbs near the pedestrian crossing. Two alternative activations for the LED system were studied: LED strips always on with constant light emission as the default state (fixed); LED strips lit with flashing light emission as the default state (flashing).
- Orange beacons: Made with a backlit LED panel, they were placed on both sides of the pedestrian crossing. Very-high-refraction film was applied above the panel, showing the symbol of the pedestrian crossing [40] and two pairs of highly bright amber flashing LEDs were specularly installed on it.

- Asymmetric enhanced LED lightning: A metal pole was installed on both sides of the pedestrian crossing, six metres high from the paved road. A die-cast aluminium lighting body was mounted on it with a white LED system and asymmetric optics focused on the zebra crossing.

Figure 1. Urban context of the experimental pedestrian crosswalk (source: Google Maps).

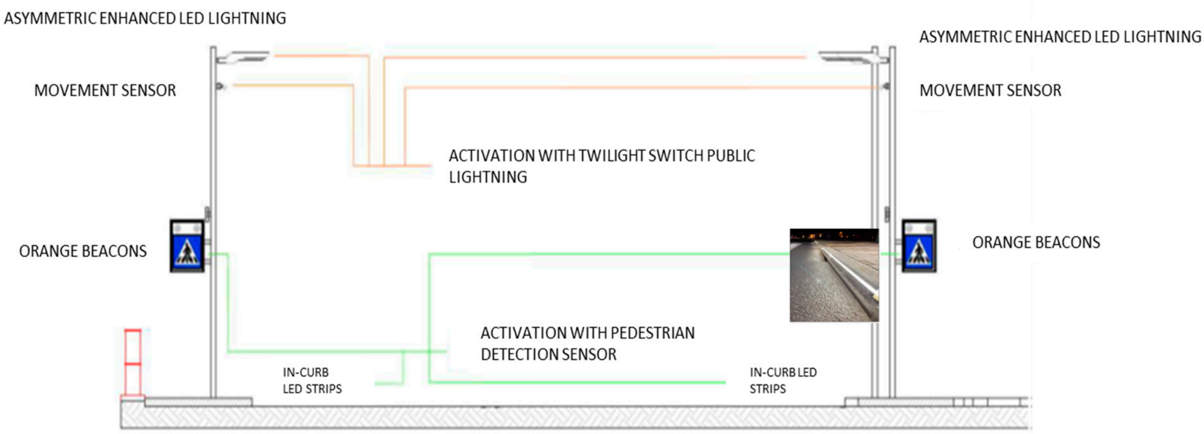

Figure 2. Section of the pedestrian crossing analysed with different lighting warning systems.

An autonomous mechanism was used as a monitoring system. The components used to operate the system were placed in a box installed on a pole of the lighting system connected to the new crossing technology. The video surveillance system consisted of two metal-optic cameras with a viewing angle of about 70 degrees, which allowed for recording colour video even in low-light conditions (Figure 3).

Through a network-switching device, surveillance cameras of the pedestrian crossing were connected to a DVR recorder with a memory capacity of about 140 GB, corresponding to seven days of video recording. The cameras and video recorder were active all night, according to the times imposed by public lighting. Both data and power were supplied and transmitted via a LAN cable.

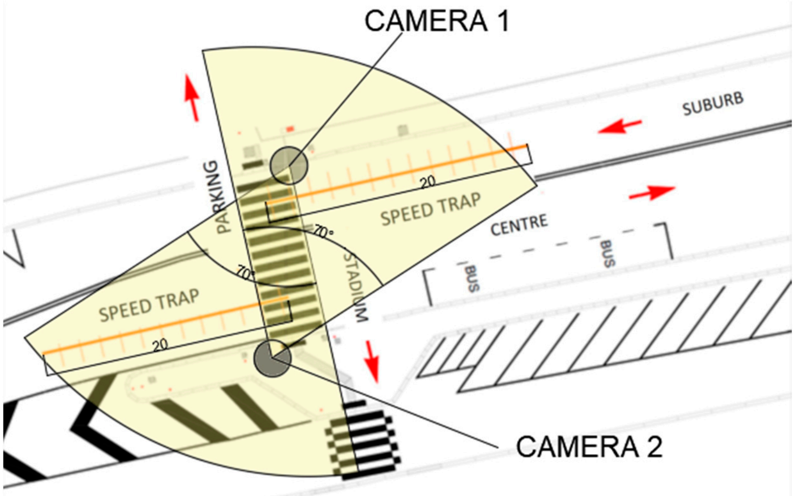

Figure 3. Crossing camera position and operating radius. The red arrows indicate the two road directions (suburb and centre), the parking area and the stadium.

The video surveillance system was placed on both sides of the pedestrian crossing to analyse the behaviour of all drivers in the seven different experimental lighting configurations of the crossing. Figure 4 shows the output of the monitoring system recorded during the night (from 7 p.m. to 6 a.m., considering seasonal fluctuations of 2 h).

Figure 4. Extracted frame showing vehicle–pedestrian interaction.

2.2. The Integrated Lighting Warning System and the Monitoring System

Figure 5 shows four phases of the study to evaluate different lighting warning systems. Starting from the standard street lighting configuration, phase 1 involved the evaluation of 7 different lighting configurations and the subdivision of smart lighting accordingly. In phase 2, the different systems were monitored continuously for five months. Phase 3 involved the analysis of video data collected to study vehicle speeds and braking distances. Finally, in phase 4 the 7 different lighting configurations were statistically compared to assess which was best suited to ensure pedestrian safety at night.

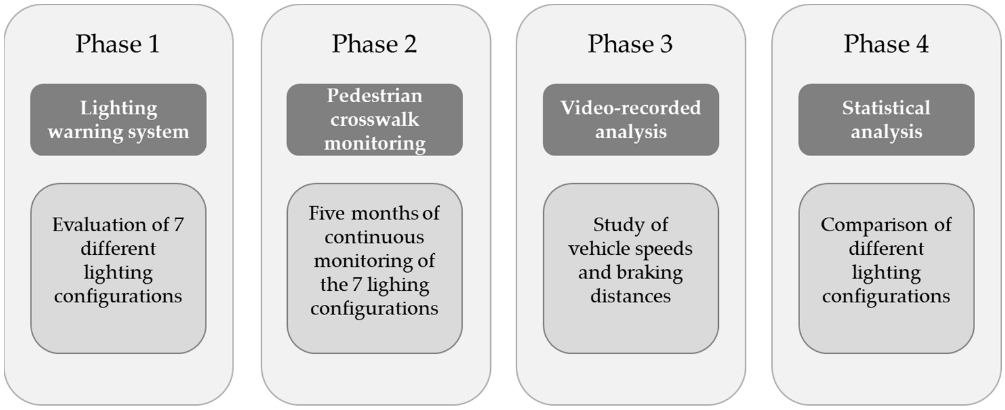

Figure 5. Steps of the study to evaluate different lighting warning systems.

Table 1 shows the seven different light configurations considered during the monitoring phase to assess the behaviour of drivers near the crossing.

Table 1. On–off status of the pedestrian crossing lighting systems in the seven conditions.

Configuration	Standard Road Lightning	Orange Beacons	Enhanced LED Lightning	In-Curb LED Strips—Fixed	In-Curb LED Strips—Flashing
0	On	Off	Off	Off	Off
1	On	On	Off	Off	Off
2	On	On	On	Off	Off
3	On	On	Off	On	Off
4	On	On	Off	Off	On
5	On	On	On	On	Off
6	On	On	On	Off	On

Equipped with a single standard streetlamp without any experimental lighting element, configuration 0 was considered the control configuration. The lighting was always active regardless of the presence of pedestrians and was the basic configuration for all subsequent experimental configurations. In configuration 1, orange beacons were added to the standard street lighting. They provided dedicated lighting with LED projectors operating only via pedestrian sensors. In configuration 2, enhanced LED lighting was added to the orange beacon system, providing an orange flashing illumination of the vertical pedestrian crossing signal. Configurations 3 and 4 reflected configuration 1 with the addition of in-curb LED strips. In configuration 3 the LED strips were fixed with constant emission (fixed). In configuration 4, the LED strips flashed (flashing). Configurations 5 and 6 resembled configuration 2 with the addition of fixed and flashing LED strips.

The first step was to define which type of pedestrian–vehicle interaction to analyse. Based on the monitoring carried out, pedestrians can be involved in different scenarios defined by the behaviour of the vehicle approaching the pedestrian crossing:

- Slowdown: once the pedestrian is detected, the vehicle slows down to allow crossing without stopping completely.
- Stop: the vehicle stopped completely to allow crossing.
- No priority: the vehicle did not stop or slow down, so the pedestrian was forced not to cross the road.

Vehicle slowing down and stopping scenarios were taken into consideration in order to obtain the following indicators:

- Speed of vehicles approaching the pedestrian crossing.
- Number of crossings, diversified by categories of users (pedestrians, cyclists).
- Percentage of correct interactions, in relation to crossing settings.

Pedestrian–vehicle interactions were monitored for five months, without considering the separate direction of vehicle flows. In order to correctly position some of the infrastructure for speed analysis, a part of the lane length was identified for each direction of travel. The time taken by vehicles to travel that section of road was measured to obtain the instantaneous speed. Considering the field of view of the camera and the results of the survey, two points on the road platform, at a distance of 20 m from the zebra crossing line, were identified for measurements. Once the reference road section was identified, the video metadata were analysed. The sampling rate used was 15.00 frames per second, equivalent to a time interval of 0.0667 s between each frame (Figure 6).

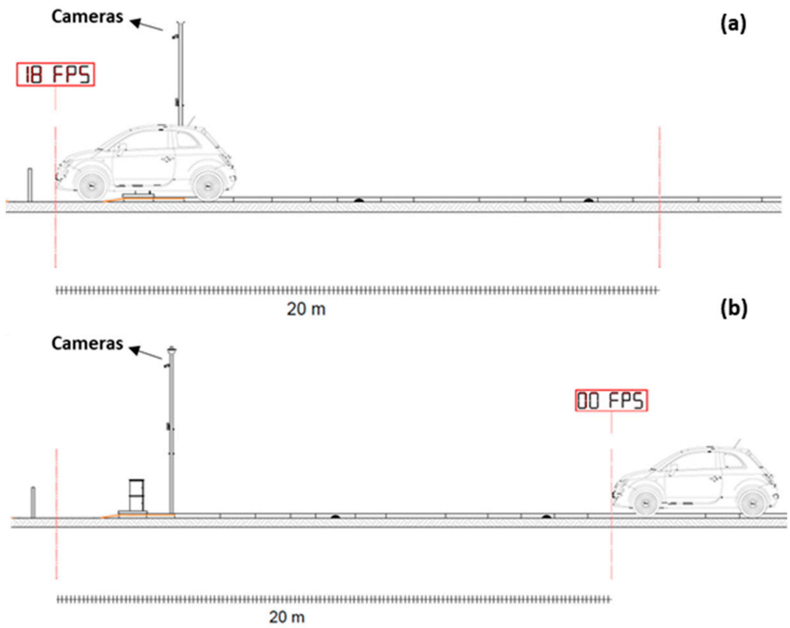

Figure 6. Detection technique for speed estimation: (**a**) entrance zone of the reference section; (**b**) exit zone of the reference section with the number of frames per second detected.

Once the time interval for each frame was identified, measurements of all pedestrian crossings with pedestrian–vehicle interaction were taken for each vehicle. The number of frames needed to cover the reference section of 20 m in the direction of travel of the vehicle was recorded. The instant speed formula was then applied, provided by the ratio between the length of the reference stroke (equal to 20 m) and the number of detected frames (fps), with the time interval between each frame equal to 0.0667 s.

The curve of the speed of approach to the pedestrian crossing was calculated using the formula of the Italian Ministerial Decree DM 2001 (MIT, 2001) [41] (1), which depends on the space covered in time τ (D_1), the braking distance (D_2), the vehicle speed at the start of braking and the final speed (V_0), final speed of the vehicle, where V_1= 0 in case of stopping, the resistance forces (aerodynamics (R_a), coefficient of surface adhesion (f_l), track slope (i), gravitational acceleration (g), and vehicle mass (m)), and the total reaction time (τ) (perception, reflection, reaction, and actuation).

$$D_A = D_1 + D_2 = \frac{V_0}{3.6} \times \tau - \frac{1}{3.6^2} \int_{V_0}^{V_1} \frac{V}{g \times \left[f_l(V) \pm \frac{i}{100} \right] + \frac{R_a(V)}{m} + r_0(V)} dV \qquad [m] \quad (1)$$

Five months of video was analysed by five independent researchers who examined the experimental crossing for all seven configurations (considering the standard configuration, 0). Every light configuration was present for 20 days. The raters were not blind to the conditions they were examining. They watched the videos and detected the speed of the vehicles approaching the reference point of 20 m. They did not participate in the choice of lighting configurations and in the final comparison of the data obtained. When the driver–pedestrian interaction met the conditions to be considered valid (i.e., the correct approach to the crossing perpendicular to the sidewalk), the type of interaction and speed were studied with the method described above.

3. Results

The analysis of the seven configurations defined the number of vehicle–driver interactions and their approach speeds. The speed of vehicles recorded at the experimental pedestrian crossing, according to the different configurations, is analysed in Table 2.

Table 2. Descriptive statistics of the speed data for the seven configurations.

Configuration	N of Interactions	Minimum Speed (km/h)	Maximum Speed (km/h)	Average Speed (km/h)		Standard Deviation	Variance
	Statistics	Statistics	Statistics	Statistics	SD	Statistics	Statistics
0	42	17.41	59.97	42.96	1.53	9.94	98.86
1	27	14.20	56.81	28.24	2.07	10.74	115.33
2	50	14.39	59.97	35.69	1.61	11.39	129.80
3	59	8.24	59.97	34.08	1.78	13.70	187.70
4	136	7.29	56.81	31.41	1.19	13.93	194.02
5	117	6.50	59.00	20.37	1.04	11.22	125.99
6	90	12.71	60.00	40.32	1.27	12.08	146.03

For each configuration, the number of interactions changed accordingly. This depended on the period of the year in which the interactions were recorded and the number of crossings that insisted on the configuration considered in the period analysed. Table 2 shows that the average speeds of configurations 1, with orange beacons (28.24 km/h), and 5, with flashing led strips (20.37 km/h), allow for a safe pedestrian crossing. A decrease in speed is evident for all configurations compared to condition 0 (standard road lighting), which has no innovative crossing elements, except for configuration 6, where the average speed is 40.32 km/h. Changes in speed data were reported for each configuration. Standard deviations show low variability in speed data between different configurations, without abnormal values. This confirms that all users, in the absence of the new lighting systems described above, were proceeding at speeds very close to the average of 42 km/h.

The speed recorded on the road under analysis was always below the 50 km/h limit. The aim of this study was to verify whether the actual speed maintained by drivers was adequate to allow safe passage for vulnerable users. The speed calculated for each pedestrian–vehicle interaction was compared to the speed vehicles should maintain to yield to pedestrians. A safe stop manoeuvre would start 20 m before the central line of the pedestrian crossing at a speed of 7 m/s (25 km/h). This condition would give a driver time to perceive the pedestrian crossing, assess the emergency manoeuvre to be performed, and safely stop within the available space. Percentages of events involving vehicles with speeds between 25 km/h and over 45 km/h analysed for each configuration are given below (Figure 7).

As shown in Figure 7, under all conditions, a higher percentage of vehicles maintain a speed of 25 km/h or even lower than the standard condition without innovative equipment. The results also show that conditions 1 (orange beacons) and 5 (enhanced LED lighting, orange beacons, and in-curb fixed LED) recorded more vehicles with speeds within the acceptable range to detect a pedestrian and to brake accordingly. From the calculation given by Formula (1), three speed classes were defined within which a driver is able to perform complete manoeuvres, partial manoeuvres, or no manoeuvres in order to stop the vehicle and let a pedestrian cross. With a speed of up to 25 km/h, a driver can perceive a user at a pedestrian crossing, assess any emergency manoeuvres to be made, and stop the vehicle safely within the available space. For speeds between 25 km/h and 35 km/h, a driver can only perceive the pedestrian crossing, assess the emergency manoeuvre to be carried out, and activate the emergency braking without completing the transitional braking phase. Finally, for speeds above 35 km/h, the driver of a vehicle is not able to perceive a user crossing the road and implement the emergency manoeuvre, since the required journey time is less than the psychophysical reaction time set at 2.10 s [18]. Figure 7 shows that, for the 25–35 km/h range, configuration 1 has the highest event rate of 34% compared to other light configurations. Although configuration 2 has a percentage of events equal to condition 6, it shows peak values in the range 35–45 km/h. In the next stage, a series of statistical tests were carried out to validate the analysed samples. As shown in Table 2, the highest speeds are in configurations 0 and 6, where the highest percentage of events occur in the range > 45 km/h (Figure 7).

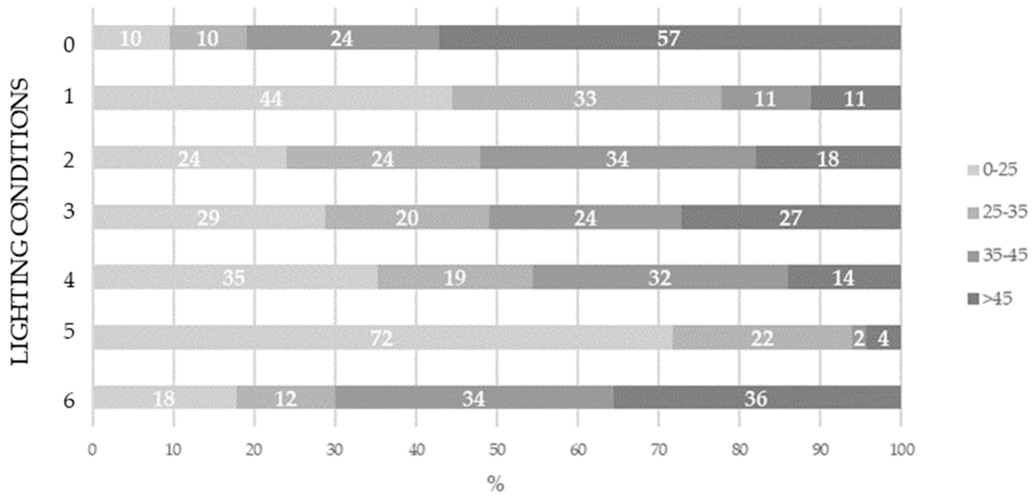

Figure 7. Percentage of events in the different speed ranges for each condition.

A one-way ANOVA was run with the seven configurations as the independent variable. This test statistically confirmed that there were significant differences among the seven configurations' average speeds. Table 3 compares all of the different configurations to find statistically significant differences that allow for the effectiveness of new experimental lighting systems in relation to speed to be validated. It has been suggested that adding a feature to the system will reduce speed. Table 3 summarises the comparison between the seven conditions, reporting the ANOVA result.

Table 3. Single-way ANOVA among the different configurations.

ANOVA	Sum of Squares	df	Mean Square	F	Sig.
Between groups	28,467.52	6	4744.58	31.22	0.000
Within groups	78,104.55	514	151.95		
Total	106,572.07	520			

The results of the ANOVA showed a significant difference between the speed of the seven configurations ($F(6, 514) = 31.22$, $p < 0.001$). To further investigate the correlation among the different configurations in terms of speed, a Scheffe post hoc analysis (Table 4) was carried out. Configuration 0 showed significant differences with almost all of the others. From configurations 0 to 5, adding new light devices, there were significant differences. By increasing the light signalling devices, the average speed decreased significantly compared to other configurations. Configuration 6, with flashing in-curb LED strips, showed an unusual trend as it did not have substantial changes compared to configuration 0. In configuration 5 (n = 117, M = 20.37, SD = 1.04), there is a significant difference in average speed compared to all of the configurations (not for configuration 1).

Table 4. Scheffe post hoc analysis.

(I) Condition		Mean Difference (I–J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
0	1	14.72 *	3.04	0.000	5.44	24.01
	2	7.26	2.58	0.106	−0.61	15.15
	3	8.88 *	2.49	0.008	1.28	16.48
	4	11.54 *	2.18	0.000	4.90	18.19
	5	22.58 *	2.22	0.000	15.82	29.36
	6	2.63	2.30	1.000	−4.39	9.67
1	0	−14.72 *	3.04	0.000	−24.01	−5.44
	2	−7.45	2.94	0.244	−16.44	1.53
	3	−5.84	2.86	0.881	−14.58	2.90
	4	−3.17	2.59	1.000	−11.11	4.75
	5	7.86	2.63	0.062	−0.17	15.90
	6	−12.08 *	2.70	0.000	−20.34	−3.83
2	0	−7.26	2.58	0.106	−15.15	0.61
	1	7.45	2.94	0.244	−1.53	16.44
	3	1.61	2.37	1.000	−5.62	8.85
	4	4.28	2.04	0.764	−1.94	10.50
	5	15.32 *	2.08	0.000	8.96	21.68
	6	−4.63	2.17	0.706	−11.27	2.01
3	0	−8.88 *	2.48	0.008	−16.48	−1.28
	1	5.84	2.86	0.881	−2.90	14.59
	2	−1.61	2.37	1.000	−8.85	5.62
	4	2.66	1.92	1.000	−3.20	8.53
	5	13.71 *	1.97	0.000	7.69	19.72
	6	−6.25	2.06	0.055	−12.55	0.059
4	0	−11.55 *	2.18	0.000	−18.19	−4.90
	1	3.18	2.59	1.000	−4.75	11.11
	2	−4.28	2.04	0.764	−10.50	1.95
	3	−2.66	1.92	1.000	−8.53	3.20
	5	11.04 *	1.55	0.000	6.29	15.79
	6	−8.91 *	1.67	0.000	−14.02	−3.79
5	0	−22.59 *	2.22	0.000	−29.36	−15.82
	1	−7.87	2.63	0.062	−15.90	0.17
	2	−15.32 *	2.08	0.000	−21.68	−8.96
	3	−13.71 *	1.97	0.000	−19.72	−7.70
	4	−11.04 *	1.55	0.000	−15.79	−6.29
	6	−19.95 *	1.72	0.000	−25.23	−14.68
6	0	−2.64	2.30	1.000	−9.67	4.39
	1	12.09 *	2.70	0.000	3.83	20.34
	2	4.63	2.17	0.706	−2.01	11.27
	3	6.25	2.06	0.055	−0.058	12.55
	4	8.91 *	1.68	0.000	3.79	14.02
	5	19.95 *	1.723	0.000	14.67	25.23

* The mean difference is significant for a *p*-value less than 0.05.

Significant changes were found among the configurations, especially between configuration 0 and the others, with a significant difference when compared to configuration 5 ($p < 0.001$), according to the ANOVA with the Scheffé post hoc analysis. Configuration 6 is distinct from a number of the other configurations in an important manner. The addition of the dedicated enhanced LED lighting and the fixed-in-curb LED device shows that the difference between configurations 0 and 5 was significant in terms of speed. This suggests that the use of all of the smart instrumentation has real effectiveness in decreasing speed.

The addition of dedicated enhanced LED lighting and a fixed in-curb LED device showed significant speed differences between conditions 0 and 5. This means that the use of smart devices had a real effectiveness in reducing speed. The use of orange beacons (configuration 1) or enhanced LED lighting, orange beacons, and a fixed in-curb LED device (configuration 5) proved to be the best for reducing speed. In any case, they did not show a significant difference in the average values. For this reason, results were interfaced with two other factors: the number of stops made or not made by drivers at the pedestrian crossing. Figure 8 shows the different types of interaction as "Stop" and "No-Stop" manoeuvres of drivers.

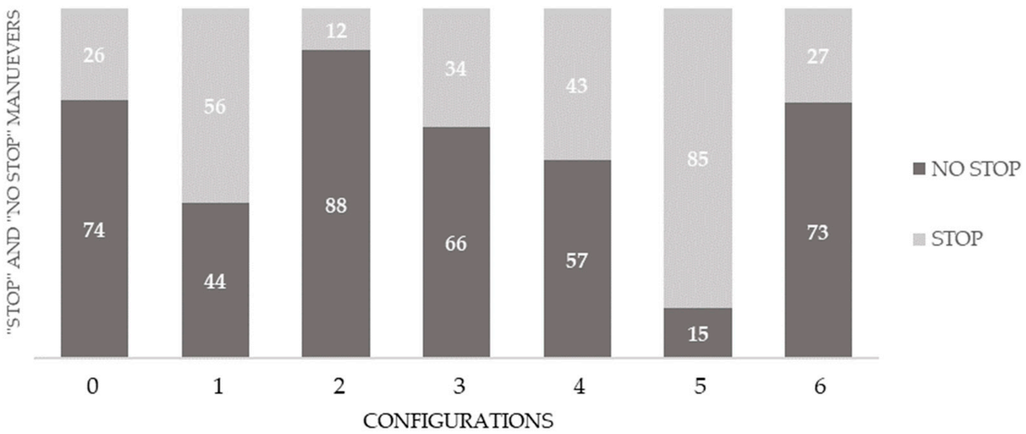

Figure 8. Percentage of vehicles' manoeuvres approaching the pedestrian crossing.

The analysis was carried out by observing the videos when drivers yielded to pedestrians crossing the road. The number of stops did not increase with the addition of innovative signalling elements near the pedestrian crossing. However, for condition 5, 85% of vehicle–pedestrian interactions allowed the pedestrian to cross, while in condition 1 only 56% were able to do so. The statistically significant speed difference previously recorded by the one-way ANOVA was due to the greater number of "stops" recorded in the interactions analysed.

4. Discussion

This study presents the analysis of data collected over five months from monitoring a pedestrian crossing. The "natural" interaction between pedestrians and vehicles was evaluated to assess which lighting configuration was the best for vulnerable road users' safety. Since neither pedestrians nor drivers were aware of participating in this study, their behaviour was not influenced by the characteristics of demand. Seven lighting configurations were analysed, including condition 0 with only standard street lighting. Configurations differed only for the activation of a different device or the specific feature of a device, such as the continuity of light emission for in-curb LED lighting.

Based on the established parameters, analysis of the collected data shows that, during the 5-month observation period, the total number of recorded crossings amounted to 519. The distribution of these crossings was not homogeneous, because both pedestrian flow and hours of darkness affected the number of observations. The average speed and standard deviation were calculated for each configuration. Speeds were always lower than that of configuration 0 (only standard road lighting and all innovative devices switched off) and the speed limit imposed on the road. The slowest speeds were reached in configuration 1 with orange beacons (n = 27, Vmean = 28.24, SD = 2.07) and configuration 5, with a fixed in-curb LED system (n = 117, Vmean = 20.37 SD = 1.04). An average speed of 40.32 km/h was recorded for configuration 6 only, similar to configuration 0. With all devices on and an in-curb flashing LED system, drivers felt safe and able to detect any passing user. For this reason, they did not slow down and maintained speeds similar to those of configuration 0. This result can also be seen in Figure 8, which shows that the percentage of vehicles stopping at the pedestrian crossing is 27%, as well as for configurations 0 and 6. The presence of lighting warning systems reduced vehicles' speed in configurations 1, 2, 3, 4, and 5, analysed compared to the standard road configuration, 0 [42,43]. Despite the different number of samples analysed for each configuration, the data show a comparable variance.

After this, it was assessed whether a driver was able to stop the vehicle at a distance of 20 m from the pedestrian crossing in relation to the driving speed maintained in the presence of a pedestrian crossing the road. Considering the braking distance, at a speed below 25 km/h a driver should be able to stop the vehicle to let a pedestrian cross the road. The results show the trend at average speeds. For each condition, there is a percentage of vehicles travelling at speeds lower than 25 km/h. This speed was higher in configurations 0 and 6.

Analysing the different lighting combinations, the use of orange beacons (configuration 1) or enhanced LED lighting, orange beacons, and fixed in-curb LED strips (configuration 5) are those able to guarantee a greater degree of road safety in terms of the speed of approach. Again, configurations 5 (72%) and 1 (44%) show a greater number of vehicles able to stop in time at the pedestrian crossing.

A one-way ANOVA test was used to validate the effectiveness of the best lighting configurations in reducing vehicle speed. The ANOVA test with a Scheffe post hoc analysis showed a significant difference among the seven configurations. This confirmed that the road lightning system influenced the speed of the drivers. This study confirmed that configuration 5 showed a significant difference with all other configurations except for configuration 1. The comparisons between these two configurations were investigated by analysing vehicle–pedestrian interactions. The percentages of "stop" and "non-stop" vehicles were evaluated. This analysis concluded that configuration 5 with 85% stops allowed more crossings than configuration 1 with only 56%.

The results obtained are in line with those of Carrese et al. [44], which show that an integrated LED lighting system generates a significant speed-reducing effect on vehicles, improving pedestrian safety at pedestrian crossings. Pena-Garcia et al. [45] also found that well-lit streets (i.e., where lighting is uniform) with improved levels of illumination make people feel safer. By inserting fixed in-curb LED strips, which are activated only when a pedestrian crosses the road, the crossing is even more visible and therefore safer.

5. Conclusions

In all cities, more attention is being paid to pedestrian safety and strengthening measures have been taken to achieve Vision Zero targets for road traffic fatalities or serious injuries [44]. In Italy, the number of pedestrians killed in road accidents was 17% (534 victims) of total road accidents in 2019 [45]. The enhanced intensity of smart street lighting increases the visibility of pedestrians at night, especially near pedestrian crossings. This type of intervention was associated with a significant reduction in night pedestrian accidents. This research analysed the impact on pedestrians of an experimental smart lighting warning system placed near a pedestrian crossing to increase road safety. The pedestrian crossing was equipped with different signalling systems controlled by pedestrian detection sensors or flashing devices: in-curb LED strips, orange beacons, and enhanced LED lighting. Two video surveillance cameras were installed on the two poles of the enhanced LED lighting system, placed at the two ends of the pedestrian crossing. With a viewing angle of about 70 degrees and a high-resolution 1920 × 1080 colour format, these cameras detected the pedestrian crossing and the part of the road platform that approaches it even in poor-visibility conditions. As streetlamps are operated by a twilight switch adjusting the voltage only at night, a 12/24 volt battery with a charger was installed in the orange beacon system with pedestrian presence detectors even during the daytime. Vehicles approaching the pedestrian crossing could see it thanks to the light beam projected by the enhanced LED lighting system and the light of the backlit panels with the symbol of the crossing. In addition to these devices, vehicles were also able to detect pedestrians entering the crossing by flashing LED orange beacons and in-curb LED strips. This articulated system appropriately warned drivers approaching a pedestrian crossing of pedestrians already engaged or about to cross it, so that they could safely adjust their speed by means of appropriate devices. For the evaluation of the best-integrated lighting system, each device was evaluated in relation to the approaching driver's behaviour. The smart lighting warning system, in combination with both orange flashing beacons and in-curb flashing LED lighting, resulted in being particularly effective in reducing the speed at night [28,38]. This research confirmed the validity of previous studies using mobile eye tracking [39,46–48]. Again, the use of enhanced LED lights, orange beacons, and in-curb LED strips (configuration 5) showed a higher percentage of permitted crossings (85%) [49]. A video (S1) of the present configuration (configuration 5) of the pedestrian crossing lighting warning system was added to the Supplementary Materials. This research also showed how lighting conditions affect vehicle performance regardless of driving or environmental conditions. The calculation of the stopping distance did not consider other factors that may affect a driver, such as pedestrian clothing, fatigue, and age of the driver. Future analyses should predict how these elements affect the stopping distance. Finally, to improve road safety, there is a need for in-depth studies on aspects closely related to pedestrian crossings, such as location, traffic volume, vehicle speed, number of pedestrians, width of the pavement, and distracting elements on the side of the road.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/smartcities7050114/s1, Video S1: The pedestrian crossing lighting warning system.

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