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Published Version:
Costa, M., Lantieri, C., Vignali, V., Ghasemi, N., Simone, A. (2020). Evaluation of an integrated lighting-warning system on motorists’ yielding at unsignalized crosswalks during nighttime. TRANSPORTATION RESEARCH PART F: TRAFFIC PSYCHOLOGY AND BEHAVIOUR, 68, 132-143 [10.1016/j.trf.2019.12.004].

Availability:
This version is available at: https://hdl.handle.net/11585/711788 since: 2020-01-07

Published:
DOI: http://doi.org/10.1016/j.trf.2019.12.004

Transportation Research Part F: Traffic Psychology and Behaviour, 68, 2020, pp. 132-143
https://doi.org/10.1016/j.trf.2019.12.004

Evaluation of an integrated lighting-warning system on motorists' yielding at unsignalized crosswalks during nighttime

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Abstract

Drivers' yielding behavior to pedestrians during nighttime was assessed in seven different conditions of crosswalk lighting: (a) baseline condition with standard road lighting; (b) enhanced LED lighting that increased lighting level from 70 to 120 lx; (c) flashing orange beacons on top of the backlit pedestrian crossing sign; (d) in-curb LED strips on the curbsides of the zebra crossing with steady light emission; (e) in-curb LED strips with flashing light emission; (d) all previous devices activated with in-curb LED strips in steady mode; (e) all previous devices activated with in-curb LED strips in flashing mode. For every condition 100 trials were recorded with a staged pedestrian that initiated a standardized crossing when a vehicle was approaching. The frequency of drivers' yielding was computed for each condition. A significant increase for yielding compliance was recorded from standard road lighting to enhanced dedicated lighting (19–38.21%), and from enhanced dedicated lighting to the seventh condition with the flashing beacons and the flashing in-curb LED strips activated (38.21–63.56%). The results showed that the integrated lighting-warning system for pedestrian crossings was effective in increasing motorists' yielding to pedestrians during nighttime.

Keywords:

Pedestrian crossing

Pedestrian safety

Nighttime road safety

Driver's vision

LED road lighting

Yielding

1. Introduction

Pedestrian risk in road crossing is a critical point in road safety. In 2016, for example, pedestrian fatalities in EU countries accounted for nearly 21.2% of all road accident deaths (European Road Safety Observatory, 2018). The percentage of pedestrian fatalities is particularly high for the elderly. In EU, for example, 47% of total pedestrian fatalities concerned persons with an age greater than 64 (European Road Safety Observatory, 2018). According to the same statistics, and in relation to the time of the day, 50% of all pedestrian fatalities occurred between 4 pm and midnight, and 7% occurred between midnight and 4 am. Furthermore, pedestrian fatalities are higher during wintertime (35% in the interval October-December, and 25% in the interval January-March) in comparison to spring- or summertime (18% in the interval April-June, and 22% in the interval July-September) (European Road Safety Observatory, 2018). This effect is probably due to the increase of darkness/twilight in wintertime and to the higher risk for pedestrians during darkness (Owens & Brooks, 1995; Owens & Sivak, 1996; Sullivan & Flannagan, 2002). In fact, pedestrian fatalities are more seasonal than all road fatalities. Also if the volume of pedestrians is much lower in the evening and night, 45% of pedestrian fatalities occurred during darkness (European Road Safety Observatory, 2018; Plainis & Murray, 2002).

Late detection of pedestrians at night is often stated as a key causal factor in pedestrian fatalities (e.g., Rumar, 1990). Sivak et al. (2007), in their analysis of five major transportation safety issue facing the United States, reported safety of night driving, particularly reducing nighttime crashes involving pedestrians, as a "major opportunity" to advance road safety. The focal visual functions that facilitate our ability to recognize and respond to infrequent, unexpected, and low-contrast hazards (including pedestrians) are severely degraded under darkness conditions (Brooks, Tyrrell, & Frank, 2005; Owens & Tyrrell, 1999).

Pedestrian safety in road crossing can be improved along three main actions: computer-aided systems for the automatic recognition of pedestrians, the increase of pedestrian conspicuity and visibility, and crosswalk design and lighting (Bichicchi et al., 2017). Our study is focused on the last two actions, proposing an integrated lighting-warning system automatically activated by the presence of a pedestrian, aimed at increasing pedestrian conspicuity and driver yielding compliance to pedestrians.

The pedestrian-centered actions are mainly aimed at increasing pedestrian conspicuity and visibility. The drivers' ability to see and respond to pedestrians at night decreases significantly when pedestrians wear clothing that does not contrast with the visual background and when they are illuminated by an approaching vehicle's low beams (Allen, Hazlett, Tacker, & Graham, 1970; Balk, Tyrrell, Brooks, & Carpenter, 2008; Shinar, 1984; Wood, Tyrrell, & Carberry, 2005). Many studies have highlighted the positive effect of wearing retroreflective markings on driver's recognition of pedestrians at night (Owens, Wood, & Owens, 2007; Tyrrell, Wood, Owens, Whetsel Borzendowski, & Stafford Sewall, 2016; Venable & Hale, 1996). These markings are particularly effective when positioned on limb joints since they move along a specific pattern, whereas if positioned on the torso they tend to be more stable, capturing lower visual attention (Owens et al., 2007). The positive effect of retroreflective markings in increasing conspicuity at night was also shown when applied to bicycle frames (Costa et al., 2017) in case of bicyclists.

Fekety, Edewaard, Stafford Sewall, and Tyrrell (2016) investigated the nighttime conspicuity benefits of adding electroluminescent panels to pedestrian clothing that included retroreflective elements. A pedestrian wearing a garment that included both electroluminescent panels and retroreflective materials is detected at a greater distance. Furthermore, emitting light, electroluminescent panels are particularly effective in increasing the conspicuity of a pedestrian that is not directly illuminated by the headlamps of an approaching driver.

The distance at which drivers are able to respond to pedestrians is also influenced by the use of high beam headlights. When low beams are used, drivers tend to respond to the presence of a pedestrian at an average distance of under 60 m, whilst with high beams the mean response distance increased to over 90 m (Wood et al., 2005). The use of high-beam headlights, however, is often impossible due to opposing and leading vehicles present. Drivers tend to use low beam headlights far more often than high beam headlights even when in conditions that are ideal for high beam usage (Buonarosa, Sayer, & Flannagan, 2008). Pedestrian tend to overestimate their own conspicuity to drivers at night. Allen et al. (1970) found that more than 95% of their participants overestimated their own visibility. Their estimates were up to three times greater than their actual visibility distances. Shinar (1984) also reported that pedestrians significantly overestimated their own visibility, with estimated visibility distances averaging 20% longer than actual visibility distances. Whetsel Borzendowski, Rosenberg, Sewall, and Tyrrell (2013) found that pedestrians' estimate of their own conspicuity did not significantly varied with changes in headlamp intensity even when only 3% of the illumination from the headlamps was present.

Focusing on crosswalk design previous studies have investigated the positive effect of introducing flashing beacons on the "Yield here to pedestrian" vertical sign. Shurbutt, Van Houten, Turner, and Huitema (2009) examined the effects of LED rectangular rapid-flash yellow beacons in uncontrolled marked crosswalks. The rectangular beacons were 15 6 cm and were placed horizontally 23 cm apart. They illuminated in a wig-wag sequence, and they alternated slow volley (124 ms on and 76 ms off per flash) and rapid volley (25 ms on and 25 ms off per flash). The system was activated when the pedestrian call button was pressed. This flash pattern violated driver's expectation and the results showed a marked increase in motorist yielding behavior when the LED rectangular rapid-flash yellow beacons were active. The same authors found that a standard overhead beacon equipment did not yield to a significant difference with a baseline condition. Turner, Fitzpatrick, Brewer, and Park (2006), presenting a summary of motorist yielding at innovative pedestrian crossing treatments reported an average yielding of 52% with the overhead flashing beacon, activated by push button by the pedestrian, with a high variability between studies (13–91%).

In-roadway warning lights consist of amber lights embedded in the pavement along both sides of the crosswalk. The lights could be activated by the pedestrian by pressing a button or through automated pedestrian detection. The lights flash at a constant rate for a set period of time. Their effectiveness is highly variable between studies with an average yielding of 66% (range: 8–100%) (Turner et al., 2006). The high-intensity activated crosswalk (HAWK) system is composed by three lamps spatially organized in an inverted triangle, that provides a sequence of flashing yellow, steady yellow, steady red, and flashing red indications. It is an experimental traffic control device that was tested by Nassi (2001), showing a yielding rate of 93%. The HAWK system, however, tends to transform an unsignalized crosswalk in a signalized crosswalk due to the steady red phase which enforces the driver to stop (Turner et al., 2006).

A previous study by Van Houten, Ellis, and Marmolejo (2008) also showed that LED flashers with an irregular flash pattern installed on pedestrian signs produced a marked increase in yielding behavior. The system was also tested in nighttime condition. Vignali et al. (2019) investigated the integration of median refuge island and flashing vertical signs in unsignalized crosswalks. Flashing beacons increased fixations to the "Yield here to pedestrian" vertical sign, and the overall system increased the distance of first-fixation to the crosswalk and the stopping distance.

Most of the previous literature has examined the effectiveness of engineering treatment during daytime and very few studies have assessed the impact of conspicuity treatments during darkness. Our study was specifically aimed at assessing yielding behavior in motorists, testing an integrated lighting-warning system for improving crosswalk conspicuity and pedestrian safety during nighttime. The system in the passive state, without a pedestrian, included a dedicated lighting and backlit "Yield here to pedestrian" vertical signs placed on both sides. In the active phase, that was triggered by a movement sensor that detected a pedestrian, there was a significant increase of the lightness level, and the activation of two devices: side-mounted flashing beacons and in-curb LED strips. While beacons acted only as a warning device, in-curb LED strips had the double function of both warning and lighting device. This is the first study that tested the use of horizontal LED strips embedded in the pedestrian crossing curbsides as a device for capturing the driver's attention and increasing the lightness level of the pedestrian.

The efficacy of the lighting-warning system was tested focusing on motorists' yielding compliance using staged pedestrians as in Shurbutt et al. (2009), Turner et al. (2006) and Van Houten et al. (2008).

2. Method

2.1. The integrated lighting-warning system

The integrated system was composed by four elements:

- Movement sensor for the detection of pedestrians near the curbside area (Fig. 1);
- Horizontal white LED strips embedded in the curb that were activated by the movement sensor. Light color temperaturewas cold white (6000K) with a spacing of 6 LED every 5 cm. The LED strips extended for 5 m for each side and were located 2.5 m at the left and 2.5 m at the right of the zebra crossing (Figs. 2 and 3). Light emission could be set either steady or flashing. Due to their positioning light emission was tangent to the zebra crossing pavement. They had no lighting incremental effect on the pedestrian when he/she was on the sidewalk, whereas they increased the pedestrian conspicuity when he/she was crossing the road.
- Backlit pedestrian crossing sign 60 60 cm surmounted by two circular LED flashing beacons. One for each side. Diameter was 10 cm. Flashing rate was 1 Hz with a 30% on and 70% off duty-cycle (Figs. 1 and 3).
- Dedicated luminaires, one for each side, positioned on a cylindrical pole with an elevation of 6 m. Light sources were LEDlamps. The lighting level was enhanced when a pedestrian was detected by the sensor, increasing from 70 to 120 lx at street level (horizontal lighting measured at the center of the crosswalk, with the sensor facing up). The default horizontal lighting level, in case of no pedestrian, was 70 lx. Light temperature color was 5700K. Light beam distribution was

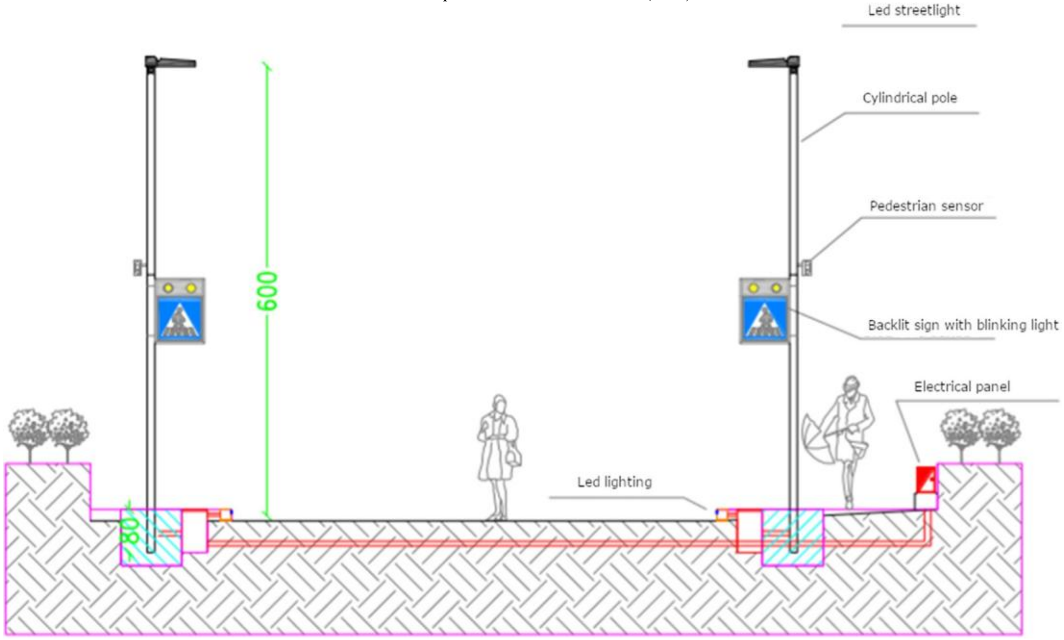

Fig. 1. Section of the experimental pedestrian crossing with the components of the integrated lighting-warning system.

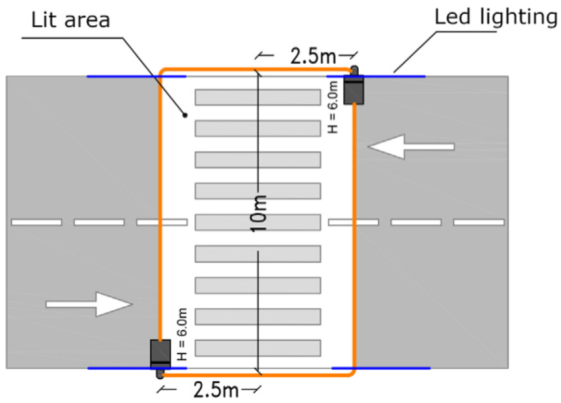

Fig. 2. Plan of the experimental pedestrian crossing with highlighted the lit area and the in-curb LED strips positioning.

Fig. 3. Components of the integrated lighting-warning system: LED strips on both curbsides of the zebra crossing; backlit pedestrian crossing sign with flashing orange lights; dedicated lighting that enhanced the light power when the sensor detected a pedestrian. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

asymmetric, inducing a positive contrast of the pedestrian. The standard road horizontal lighting level outside the experimental pedestrian crossing was 16 lx at street level, with measurement at the center of the road, directly perpendicular to the luminaire pole, and with the sensor facing up (Figs. 1 and 3).

Two alternative activations were available for the in-curb LED strips:

- The LED strips were off as default state and turned on when a pedestrian was sensed. They stay on for 15 s and thenturned off if no other pedestrians triggered the sensor.
- The LED strips were turned on with a steady emission as default state and started to flash when the sensor detected apedestrian. Flashing rate was 1 Hz with a duty-cycle of 50% on and 50% off. The activation stopped after 15 s if the sensor did not detect other pedestrians.

2.2. Procedure

The system was installed on a pedestrian crossing along Via del Triumvirato in Bologna. The road connects one of the main through road of Bologna (Via Emilia) with the bypass road system and the airport, and therefore the traffic volume is rather high. The pedestrian crossing is positioned along a straight segment of 653 m connecting a signalized intersection with a roundabout (Fig. 4). The road is a single carriageway with two lanes. Each lane width was 5.35 m for a total width of 10.7 m (Fig. 5). The pedestrian crossing serves a residential area and two bus stops, one in each direction.

Drivers' yielding compliance to pedestrians was investigated considering the seven conditions summarized in Table 1. In all conditions the standard road lighting and the backlighting of both pedestrian crossing signs were always activated.

In condition 1, which served as a control condition, only the standard road lighting and the backlighting of the lateral pedestrian crossing signs were activated (Video 1). The lighting level at the zebra crossing was 16 lx. These devices were

Fig. 4. Urban context in which the crosswalk under study (red frame) was located. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 5. Aerial view of the experimental pedestrian crossing considered in the study.

Table 1

On/off status of the pedestrian crossing components in the seven experimental conditions.

Condition	Standard road lighting	Enhanced dedicated lighting	Orange flashing beacons	In-curb LED lighting
1	On	Off	Off	Off
2	On	On	Off	Off
3	On	On	On	Off
4	On	On	Off	On (steady)
5	On	On	Off	On (flashing)
6	On	On	On	On (steady)
7	On	On	On	On (flashing)

always active, independently from the presence of a pedestrian. In condition 2 the enhanced dedicated lighting was added to the standard road lighting. The pedestrian crossing lighting level at the street level was 70 lx in case of no pedestrian and 120 lx in case the sensor was activated by a pedestrian (Video 2). Fig. 6 displays an image of the crosswalk from the point of view of the driver in condition 2.

Condition 3 included the lighting system of condition 2 with the only addition of the flashing orange beacons on top of the pedestrian crossing signs (Video 3). The beacons were activated by the sensor. Condition 4 included the setup of condition 2 with the additional activation of the in-curb LED strips with steady emission, without flashing (Video 4). Fig. 7 shows an image of the crosswalk from the point of view of the driver with the in-curb LED strips activated. Condition 5 mirrored condition 4 with the exception of the modality of in-curb LED lighting that was flashing and not steady (Video 5). Condition 6 mirrored condition 4 with the addition of the orange flashing lights (Video 6). Similarly condition 7 mirrored condition 5

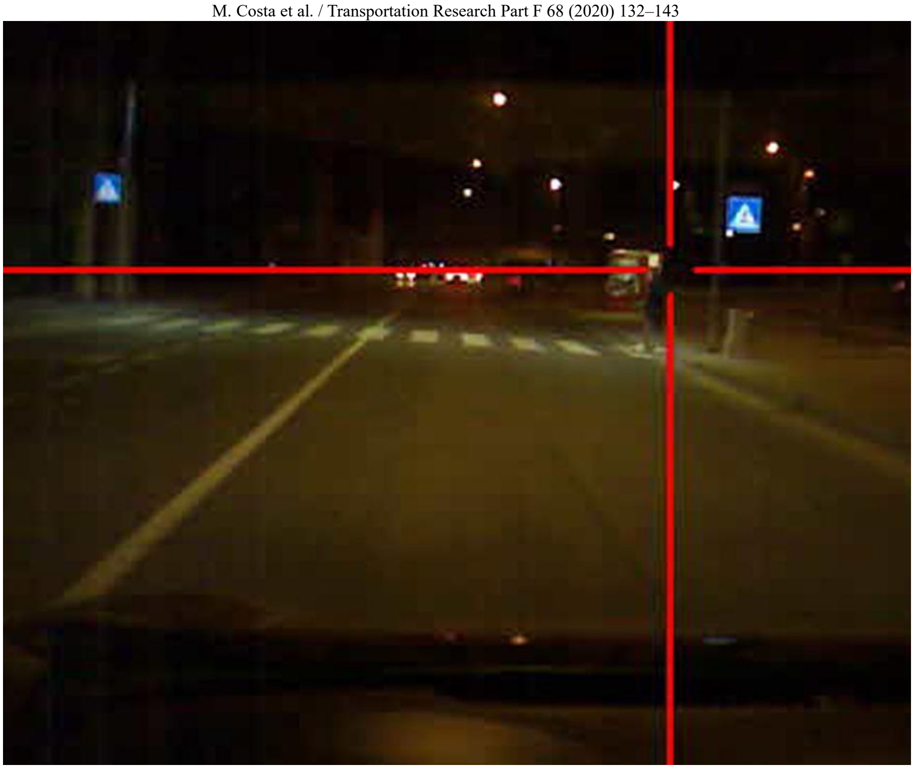

Fig. 6. Pedestrian crossing in condition 2 (enhanced lighting) from the point of view of the incoming driver. The red cross shows an ocular fixation of the driver towards the pedestrian. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

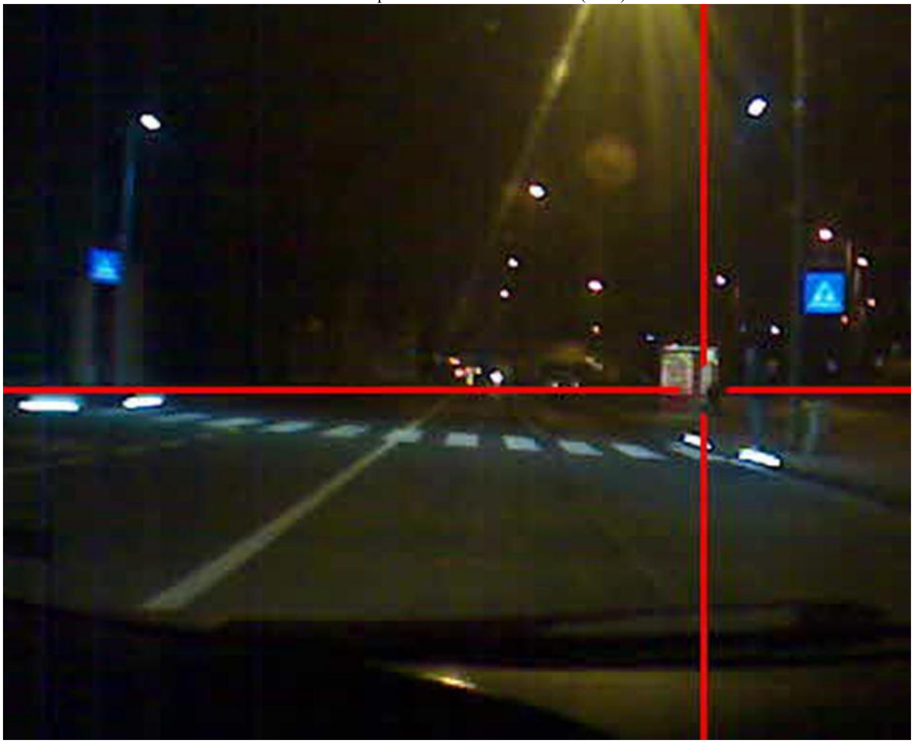

Fig. 7. Driver's point of view of the crosswalk with enhanced lighting and in-curb LED strips activated. The red cross shows the position of an ocular fixation near the pedestrian. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

with the addition of the orange flashing beacons (Video 7). In conditions 6 and 7 all the devices were activated, with the only difference that in condition 7 the in-curb LED light emission was intermittent whereas in condition 6 the emission was continuous. The flashing timing of the beacons and the in-curb LED strips was the same (1 Hz), they however operated on separate electronic timers with slightly different settings so that although they were in synchrony in the first seconds after activation, they progressively run out of phase (Video 7).

The incremental activation of only one device between the conditions allowed a precise estimate of the effect of each single element. Mean hourly traffic volume during the investigation (7–10 p.m.) was 510 ($SD = 40.59$) northward, and 240 ($SD = 64.71$) southward. V85 (85th percentile speed) during the investigation (7–10 p.m.) was 43 km/h northward and 68 km/h southward. A two-sample t-test that compared speed for all vehicles in the two directions was significant: $t\ (960) = 30.91$, $p < .001$. The distribution of road users in speed classes in both directions is reported in Fig. 8.

In order to assess yielding compliance of incoming drivers to the experimental pedestrian crossing we run 100 valid trials in each condition in which a staged pedestrian activated the sensor while a vehicle was approaching and tried to cross the crosswalk according to a standardized procedure. The staged pedestrian was initially placed on the sidewalk in a rear position so not to activate the sensor. When he was warned by an acoustical sign that a driver was approaching at a distance of 60 m, the confederate immediately walked toward the curbside activating the sensor, and entered with both feet in the beginning of the pedestrian crossing, on the margin of the zebra crossing, gazing directly to the approaching driver.

If the driver slowed down and yielded to the confederate, then the pedestrian crossed the road. In case the driver did not slow down and did not yield, then the confederate pedestrian stepped back to the sidewalk. Experimental crossings were performed alternatively in both directions. A trial was considered valid if these conditions were met:

- Good weather conditions, without fog or rain that would adversely affect the pedestrian's visibility;
- Only one pedestrian in the crosswalk;
- Driver not at a short distance from a vehicle ahead;
- Low traffic density in both directions without congestion;
- No buses stopping in the two bus stops near the pedestrian crossing;– Driver not a bicyclist.

The pedestrian was dark dressed (dark brown, dark blue, dark gray clothes, see the Video 1 through 7 for an example) and was chosen with rotation within a pool of five confederates. The pedestrian was not blind to the experimental condition since it could be inferred by the lighting-warning configuration. Every care was assured for each pedestrian to conform to the standard protocol in each condition. All experimental crossings were recorded by a hidden high-resolution video camera for further analysis. The experimental crossings were run in three separate sessions with similar traffic and whether conditions.

2.3. Data analysis

Two independent researchers examined the video recordings of the experimental crossings for all the seven conditions. For each trial and condition the two independent raters recorded if the trial met the conditions for being considered

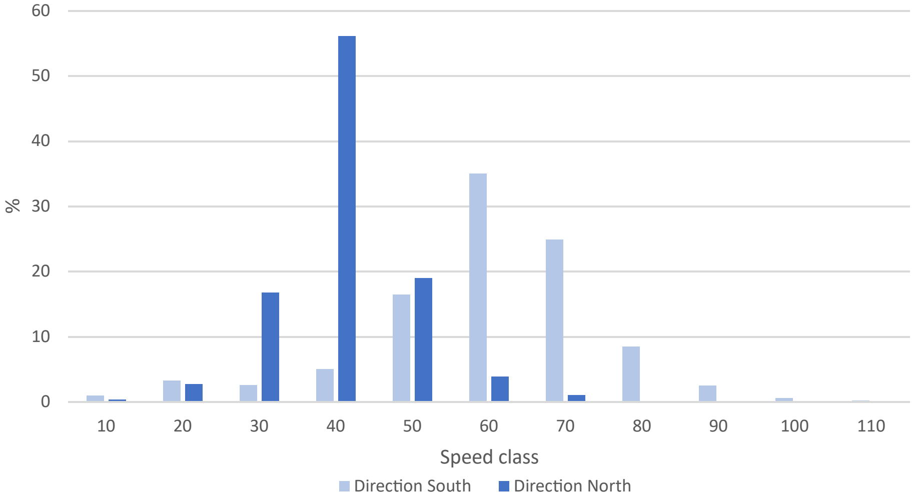

Fig. 8. Speed class distributions for North and South directions.

valid (i.e., correct behavior of the staged pedestrian, and correct context for the incoming driver), and if the driver yielded or not to the pedestrian. The raters were not blind to the condition they were examining since the condition could be inferred by the scene. Inter-rater reliability (Spearman correlation) was $r = 0.98$. Finally, the mean frequency of yielding compliance for each of the seven conditions and for each direction (North, South) was computed. The significance of the differences between yielding compliance across the seven conditions was tested with a Chi-square test. The same test was also used to verify if the yielding compliance in the different conditions was influenced by the direction (drivers travelling southward vs. drivers travelling northward). Two-proportion z-tests were computed for testing the relevant pairwise-comparisons, considering a one-sided hypothesis (the addition of a feature in the system was hypothesized to have an incremental effect in yielding rate). A Bonferroni correction was applied for taking into account the multiple pairwise-comparisons. The significance level was therefore set to $p = .007$. Phi was computed for goodness of fit and effect size proxy for the Chi-square tests. For the pairwise-comparisons the odds ratio was computed as ratio between the two proportions of yielding compliance between the two conditions under examination.

3. Results

The Chi-square test that contrasted yielding compliance in the two directions (northward and southward) and in the seven conditions was not significant ($p = .10$). Therefore, driver's approaching direction was not considered in the following analyses.

The mean frequency of yielding compliance in the seven conditions examined in this study are showed in Fig. 9. The overall Chi-square test of the cross-tabulation table was significant: $v^2 = 46$, $p < .001$, $u = 0.24$. Table 2 summarizes all the pairwise-comparisons between the seven conditions, reporting the result of the two-proportion z-test along with p and the odds ratio (ratio between the two yielding compliance ratios). In the baseline condition, with the standard road lighting only 19.00% of drivers yielded to the pedestrian. The addition of the dedicated enhanced lighting increased the yielding compliance to 38.21% (odds ratio: 2.01), and the difference between condition 1 and 2 was significant: $v^2 = 8.86$, $p = .001$.

Adding the orange flashing beacons did not significantly improve the yielding frequency ($p = .81$). Also the addition of the in-curb LED lighting with steady emission (37.96%) did not significantly increase yielding compliance in comparison to condition 2 ($p = 1$). The activation of the flashing in-curb led lighting resulted in a yielding compliance of 43.90%, that was however not significantly different from the frequency recorded in condition 2 (enhanced lighting) ($p = .50$). The combined activation of the orange flashing lights and the in-curb LED lighting with steady emission resulted in a yielding frequency of 45.45% that was also not significantly higher than that recorded in condition 2 with standard road lighting and dedicated enhanced lighting ($p = .44$).

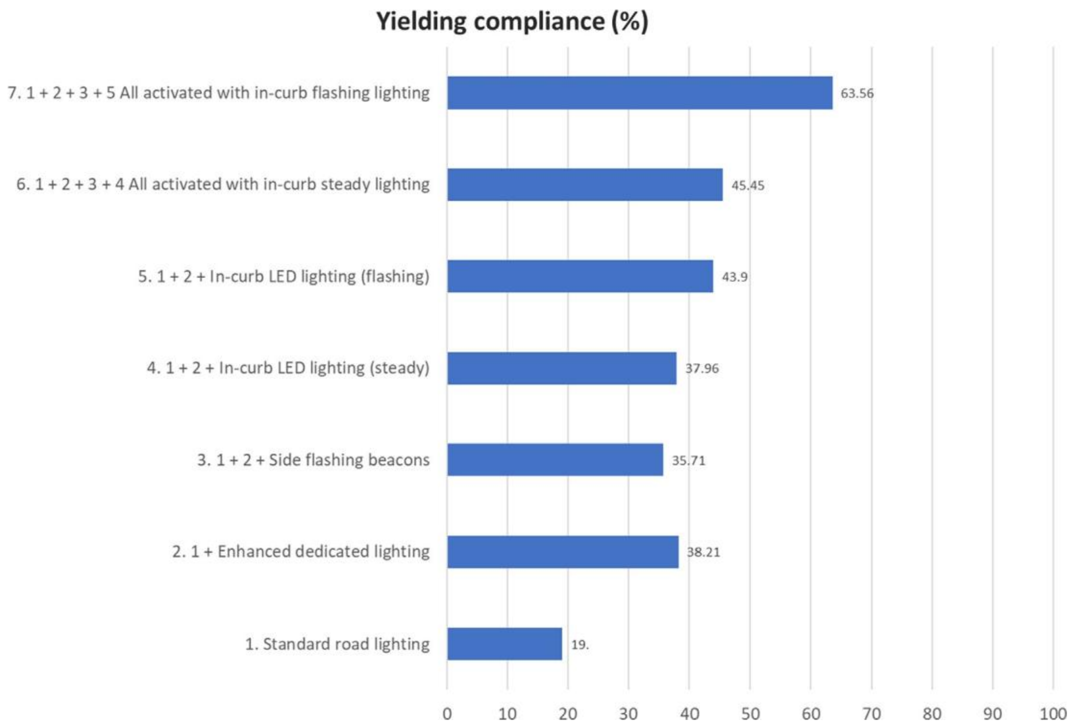

Fig. 9. Percentages of motorist yielding compliance to a pedestrian in the seven experimental conditions.

Table 2

Z-test pairwise-comparisons between the seven conditions examined in the study. OR is the odds ratio (ratio between the two yielding compliance ratios).

	1. Standard road lighting	2. 1 + Enhanced lighting	3. 1 + 2 + Flashing beacons	4. 1 + 2 + In-curb lighting (steady)	5. 1 + 2 + In-curb lighting (flashing)	6. 1 + 2 + 3 + 4 All activated with in-curb steady lighting	7. 1 + 2 + 3 + 5 All activated with in-curb flashing lighting
1. Standard road lighting		χ^2= 8.86 p = .001 OR = 2.01	χ^2 = 6.35 p = .005 OR = 1.87	χ^2 = 8.19 p = .002 OR = 1.99	χ^2 = 14.42 p = .005 OR = 1.87	χ^2 = 15.43 p < .001 OR = 2.36	χ^2 = 40.3 p < .001 OR = 3.34
2. 1 + Enhanced lighting			n.s.	n.s.	n.s.	n.s.	χ^2 = 13.70 p < .001 OR = 1.97
3. 1 + 2 + Flashing beacons				n.s.	n.s.	n.s.	χ^2 = 15.86 p < .001 OR = 1.77
4. 1 + 2 + In-curb lighting (steady)					n.s.	n.s.	χ^2 = 13.07

		$p < .001$ OR = 1.67
5. 1 + 2 + In-curb lighting (flashing)	n.s.	χ^2 = 8.09 p = .002 OR = 1.44
6. 1 + 2 + 3 + 4 All activated with in-curb steady lighting		χ^2 = 6.44 p = .005 OR = 1.39

Condition 7, which included standard road lighting, enhanced lighting, orange flashing beacons, and the flashing in-curb LED lighting, registered the highest frequency of yielding compliance (63.55%). This frequency was significantly higher than those of all the other conditions, as reported in Table 2.

4. Discussion

Pedestrian crossings alone are not sufficient to cross safely if not integrated with adequate equipment, as also shown by the Federal Highway Administration (Zegeer, Stewart, Huang, & Lagerwey, 2005) and by our study. In fact, in the baseline condition with standard road lighting, the yielding compliance was only 19.00%. Our study specifically tested the efficacy of a composite lighting-warning equipment for the improvement of pedestrian conspicuity and safety at crosswalks during nighttime. The equipment was composed of three devices: (a) dedicated luminaires; (b) orange flashing beacons positioned on top of the ‘‘Yield here to pedestrians” signs; (c) in-curb LED strips on the curbsides of the zebra crossing. For the evaluation of the integrated system it was necessary to test the contribution of each single device in relation to the approaching driver's behavior.

Therefore, we have created a set of conditions that differed for the activation of only one device or a specific property of one device, as the continuity of light emission in curb LED lighting. The dependent variable was the yielding compliance of the driver approaching the crosswalk when a staged pedestrian was present at the beginning of the zebra crossing. In order to reach a high standardization, pedestrians were confederates of the experimenters that shared the same degree of visibility of the clothes, and that were instructed to cross following a standardized procedure.

According to the procedure the pedestrian was positioned near the crosswalk and walked to the curbside, activating the sensor, when the driver was at 60 m distance. The pedestrian explicitly expressed his intention to cross putting his feet on the zebra crossing margin, just beyond the curbside, and gazing directly to the driver. The sensor activated the lighting devices that were specific for a particular condition. This procedure allowed the driver a high degree of freedom in terms of yielding, and a high differentiation between the conditions. A procedure in which the pedestrian stand still on the sidewalk near the zebra crossing could be ambiguous in relation to the intentionality of the pedestrian to cross, probably resulting in a ‘‘floor effect'', independently from the specific lighting-warning setting, whereas a condition in which the pedestrian had a more ‘‘assertive'' behavior in which he/she started to cross without observing the driver's behavior would probably have resulted in a ‘‘ceiling effect'', in which every driver yielded to all pedestrians independently from the lighting-warning setting.

The results showed two main effects. The first was the incremental effect of the enhanced dedicated lighting with a doubling of yielding compliance (38.21% versus 19.00%). The second main result was the incremental effect of the condition in which all devices were activated, and the in-curb LED lighting was in a flashing state. The magnitude of the effect (odds ratio) was 1.66 in comparison to the condition with enhanced dedicated lighting only (63.56% versus 38.21%), and 3.34 in comparison to the baseline condition with standard road lighting only. In condition 7 the orange flashing beacons, and the flashing in-curb LED lighting were switched on in addition to the enhanced dedicated lighting.

The sole addition of the orange flashing lights or, in alternative, of the sole in-curb LED lighting, either with continuous or flashing light emission, did not significantly enhanced driver's yielding compliance in comparison to a condition of enhanced dedicated lighting. The positive effects of enhanced dedicated lighting could be due to the specific properties of the luminaires used in this study that included cold white light, a lighting level that reached 120 lx at street level, a shift in lighting level from 70 to 120 lx when the pedestrian activated the sensor, and an asymmetric beam that illuminated the pedestrian in positive contrast (Tomczuk, Jamroz, Mackun, & Chrzanowicz, 2019).

In condition 7 the “warning”, and visual-attentional capture was promoted by the simultaneous activation of two flashing devices: the orange lamps on top of the pedestrian crossing lateral signs and the in-curb LED strips. Their combined effect resulted in an incremented yielding compliance of 25.35%. Flashing lights are particularly effective as a bottom-up system to alert a driver about a potential danger (Vignali et al., 2019), and flashing lights are particularly effective in capturing visual attention when presented in the visual peripheral field which is more sensitive to the perception of movement and transient changes (Costa, Bonetti, Vignali, Lantieri, & Simone, 2018). The potential of flashing lights to capture drivers’ attention was also tested by Lenné et al. (2011) who showed that flashing lights resulted in a significant increase in drivers stopping at a passive level crossing in comparison to a condition with traffic sign alone.

The flashing pattern for the beacons and the in-curb LED strips was regular and was 1 Hz for both devices. It can be suggested that a more complex and irregular flashing pattern would have increased the yielding compliance. Previous studies that have tested the high-intensity activated crosswalk (HAWK) (Turner et al., 2006) and the use of wig-wag flashing patterns with alternation of short and long volleys (Shurbutt et al., 2009) have found a very high motorists’ yielding compliance (93% and 81.5%, respectively).

The in-curb LED lights were cool white. This light spectrum was chosen in order to increase the lighting level of the crosswalk, and therefore promote pedestrian’s conspicuity. However, in the flashing condition, the in-curb LED lighting had more a warning than a lighting purpose. According to the Italian code (Italian Highway Code, 1992), all warning flashing lamps have to be amber and not white. This resulted in a possible confounding factor for motorists that should be better addressed in a future research in which the data obtained with the white in-curb LED lighting could be compared with the orange incurb LED lighting. The use of orange in-curb LED lights would match with the flashing orange beacons applied on the “Yield here to pedestrian” signs, increasing consistency and coherence of the crosswalk design.

Lighting and warning devices for road use have usually a punctiform light source whereas in this case a succession of LEDs produced a linear contour that could be useful for outlining the shape of an obstacle or delimiter in the road. LED technology offers now easy-to -use, low-cost and very efficient LED strips that could be used both for lighting or/and for delimiting and warning purposes. Specifically, in-curb LED strips could direct the driver’s attention to curbsides where pedestrians are more likely to be positioned. LED strips could be integrated in systems for traffic safety in order to increase the conspicuity of obstacles and direct the driver's attention to critical points.

Although the pedestrian safety issues are universal, the specific results have to be interpreted considering the Italian context in which drivers mainly yield when the pedestrian initiates the crossing maneuver and enter the crosswalk. It is well possible that in other countries with a higher or lower yielding compliance to pedestrians the results could differ. Both driver's and pedestrian's behavior, in fact, are highly influenced by cultural expectations and specific cognitive schemes and learning experiences (Hamed, 2001; Sueur, Class, Hamm, Meyer, & Pelé, 2013). Future longitudinal studies are needed to track if the effects highlighted in this study tend persist on a long-time run. The configuration of in-curb LED strips with both steady or flashing operating mode is new and not expected by drivers since it not included in the Italian Highway Code within the possible features that could be applied to crosswalks in order to increase their safety. Furthermore, the experimentation was conducted on only one site. Additional studies could test the efficacy of the integrated lighting-warning system in a more ample sample of crosswalks differing for their location, traffic volume, speed, pedestrian volume, crosswalk width and roadside distractions.

Overall it is possible to conclude that the integrated lighting-warning system, in the modality with both the orange flashing beacons and the flashing in-curb LED lighting, it is highly effective in increasing yielding compliance to pedestrians during nighttime conditions. Future studies could track the driver's speed when approaching the pedestrian crossing in the different lighting-warning conditions and assess the distance at which the pedestrian is first fixated and glanced by the drivers using a methodology of eye movement recording as in Costa, Simone, Vignali, Lantieri, and Palena (2018), Costa et al. (2019), and Lantieri et al. (2015). The measure of yielding compliance, in fact, cannot disentangle cases in which the driver has detected the pedestrian but has decided not to yield from cases in which the driver has not detected the pedestrian. An investigation with eye-movement recording could better explore this distinction, determining exactly when and at what distance drivers tend to detect the pedestrian, with and without the integrated lighting-warning system.

Acknowledgements

We would like to thank Federico Paveggio, engineer at the Mobility Department of the Municipality of Bologna, for the proposal to investigate the integrated lighting-warning system and his assistance in collecting the data, and

Marco Zambelli from Zama Impianti, for installing and setting the experimental crosswalk. We are also grateful to Arianna Zapparata, Lauro Mazzoni and Luigi Rossi for their assistance in collecting and analyzing the data.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trf.2019.12.004.

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