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# Flashing in-curb LEDs and beacons at unsignalized crosswalks and driver's visual attention to pedestrians during nighttime

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## ABSTRACT

Driver's visual attention (eye movements) and driving behaviour (kinematic data) were assessed when approaching an experimental crosswalk that included flashing white in-curb LED strips, flashing orange beacons, backlit 'Yield here to pedestrians' vertical signs, and enhanced lighting when a staged pedestrian attempted to cross. An experimental condition in which all devices were active was compared with a control condition in which only enhanced lighting and backlit vertical signs were active. The results showed a significant increase of motorists' yielding compliance, distance of first fixation to the pedestrian area, standard deviation for horizontal eye movements in the experimental condition. The introduction of flashing in-curb LED strips and flashing orange beacons proved to be very effective in increasing the night-time safety of the pedestrian crossing.

**Practitioner summary:** The study investigated the effects of flashing in-curb LED strips and beacons on driver's visual attention (eye movements) and speed when approaching a crosswalk during night-time. The results showed that the combination of these flashing devices significantly increased yielding compliance and the distance of pedestrian detection.

**Abbreviations:** ANOVA: analysis of variance; EU: European Union; HAWK: high intensity activated crosswalk system; LED: light-emitting diode; PHB: pedestrian hybrid beacons; ROI: region of interest; RRFB: rectangular rapid flashing beacons; UK: United Kingdom; US: United States

## KEYWORDS

pedestrian crossing; pedestrian safety; nighttime road safety; driver's vision; LED road lighting

In this paper we tested an experimental pedestrian crossing that implemented flashing white LED strips embedded in the curbs and flashing orange beacons positioned over the 'Yield here to pedestrians' signs for capturing the driver's attention to pedestrians. The aim was to test if the crosswalk lighting design could improve pedestrian safety during night-time.

Globally, pedestrians represent 22% of all road deaths and in some countries this proportion is as high as two thirds (World Health Organization 2013). Most pedestrian collisions occur when pedestrians are crossing the road (Damsere-Derry et al. 2010), and night-time travel is one of the greatest risks for pedestrians (Griswold et al. 2011; Owens and Brooks 1995; Owens and Sivak 1996). Twilight and the first hour of darkness typically see a high frequency of pedestrian collisions (European Road Safety Observatory 2020; Griswold et al. 2011). In EU countries, for example, 31% of all pedestrian fatalities occurs in the interval 48 p.m. and 50% of all pedestrian fatalities occur in the interval 412 p.m. (European Road Safety Observatory 2020). The key role of darkness in pedestrian vulnerability is also inferred considering that 35% of pedestrian fatalities are recorded from October to December, whereas from April to June the percentage drops to 18% (European Road Safety Observatory 2020). Although the frequency of pedestrians is lower, 45% of pedestrian fatalities are recorded during darkness (European Road Safety Observatory 2020; Plainis and Murray 2002), and a main factor is a late detection of the pedestrian (e.g., Rumar 1990). During darkness the ability to react to unexpected, infrequent, and low-contrast stimuli (as pedestrians), is severely impaired (Brooks, Tyrrell, and Frank 2005; Owens and Tyrrell 1999).

National statistics in the UK (Department of Transport UK 2020), showed that the distribution of pedestrian fatalities during crossing was: 14% in zebra crossings, 48% in pelican crossings, 32% in light controlled junction with pedestrian phase, 6% in crossings with human control. Considering all severities (killed, seriously injured, and slightly injured), the distribution was: 30% in zebra crossings, 33% in pelican crossings, 30% in light-controlled junction with pedestrian phase, and 7% in crossings with human control. A similar value (34%) of accidents involving pedestrians occurring at marked pedestrian zebra crosswalks was found by Olszewski et al. (2015) analysing accidents in Poland.

According to Jermakian and Zubry (2011), who analysed crash records that involved pedestrians from 2005 to 2009 in the US, the pedestrian location was in crosswalk for 21.6%, in intersection (not in crosswalk) for 27%, in non-intersection for 47.8%, and in unknown location in the remaining 3.6%. In the great majority of cases (95.5%) the accident occurred with the pedestrian crossing the road, and only in 4.5% of accidents the pedestrian was moving in-line with the traffic.

Road and crosswalk design could greatly improve pedestrian safety. Road widening, for example, strongly increases pedestrian injury risk (Noland and Oh 2004; Sawalha and Sayed 2001), whereas reducing the number of lanes has a positive impact on pedestrians' and cyclists' safety (Huang, Stewart, and Zegeer 2002). Slow and narrow streets tend to experience low rates of vehicle-pedestrian crashes, while wide travel lanes with higher operating speeds tend to experience higher rates (Gårder 2004). An effective system to reduce lane width is the introduction of a median refuge island, with the additional advantage of dividing the crossing distance in multiple segments, creating intermediate safe areas (Vignali et al. 2019; Bichicchi et al. 2017). Liu et al. (2011) tested the effect of transverse rumble strips, finding a reduction by 25% of carpedestrian crashes. Uncontrolled intersections are more dangerous than controlled intersections, since the conflicts between vehicles and pedestrians are increased (Elvik et al. 2009).

Several methods of prompting drivers at crosswalks have proven to be effective in controlling motorist behaviour. Van Houten (1988), for example, has tested advanced stop lines to prompt motorists to yield further back from the crosswalk. Huybers, Van Houten, and Malenfant (2004) have evaluated the combined effects of advance pavement markings and advance road signs. Pavement markings had a relevant effect in increasing yielding distance than sign alone.

A line of research has explored solutions for increasing the crosswalk and the pedestrian conspicuity with the use of irregular flashing patterns in warning lights. Shurbutt et al. (2009), for example, have tested LED rectangular rapid-flash yellow beacons in uncontrolled crosswalks. The beacons were 156 cm in size, 23 cm apart. They could operate with a wig-wag sequence, alternating slow (124 ms on and 76 ms off per flash), and rapid activations (25 ms on and 25 ms off per flash). The pedestrian activated the system with a call button. The irregularity of the flash pattern resulted in a marked increase in motorist yielding behaviour, whereas a standard overhead beacon equipment had no effects. The attention-capturing effect of irregular flashing patterns was also tested by Van Houten, Ellis, and Marmolejo (2008), who showed an increase in yielding compliance to pedestrian in comparison to LED flashers with regular pattern. 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.

Amber lights embedded in the road pavement at both sides of the zebra crossing, activated by the pedestrian with a call button, have shown a highly variable effectiveness with an average yielding to the pedestrian of 66% (range 8–100%). An experimental system that has proven to be very effective is the high-intensity activated crosswalk (HAWK) system, composed by three lamps arranged in an inverted triangle. The lamps are activated according a sequence of flashing yellow, steady yellow, steady red, and flashing red patterns. Nassi (2001) showed that the HAWK system increased the yielding compliance to 93%. This result can also be explained considering that the HAWK system tend to change the crosswalk from unsignalized to signalised (Turner et al. 2006).

Costa et al. (2020) have recently tested an integrated warning-lighting system for increasing the safety at unsignalized crosswalks during night-time. The system was composed by an enhanced dedicated lighting, in-curb white LED strips that could be either flashing or steady, backlit 'Yield here to pedestrians' vertical signs, and a pair of flashing orange beacons installed over the vertical signs. A sensor detected the pedestrian and activated the system for increasing the conspicuity of the pedestrian and alerting an incoming driver. The system was tested in seven conditions, with the conditions differing for the progressive activation of the different elements of the integrated warning-lighting system. The motorists' yielding rate was tested in each condition with 100 crossing attempts, in which a staged pedestrian tried to cross

according to a standardised procedure. The results showed a significant increase in motorists' yielding when the dedicated enhanced lighting was activated by the pedestrian. In this case the yielding compliance increased from 19% to 38.21%. The yielding compliance was further significantly increased when the flashing in-curb LED strips and the orange flashing beacons were activated. In this configuration yielding compliance increased from 38.21% to 63.56%.

In this study we tested the same integrated warning-lighting system that was investigated by Costa et al. (2020), with the aim of studying the driver's visual attention to the crosswalk during the approaching phase using an eye-movement recording technique. Starting from the results of Costa et al. (2020) we contrasted a control condition in which only the dedicated enhanced lighting was active to an experimental condition in which the flashing in-curb LED strips and the orange lateral beacons were added to the enhanced lighting.

Participants to the study were unaware of the aims and had to travel a fixed route that included the integrated warning-lighting system while their eyemovements and the car kinematic data were recorded. This experimental design allowed to investigate the time-course of the driver's visual attention when approaching to the crosswalk and if the crosswalk design promoted an advantage in visual detection of the pedestrian. Furthermore, the synchronisation of the car kinematic data with the eye-movement data allowed the study of how visual attention influenced driver's behaviour.

We suggested that the activation of the two flashing devices would affect the driver's eye scanning behaviour approaching the pedestrian crossing, the distance of first visual detection of the pedestrian, the slowing distance, and the motorist's yielding rate to pedestrians.

## Method

### Participants

Participants were 13 drivers in the control condition and 17 drivers in the experimental condition. In the control condition 7 drivers were females ( $M_{age} = 24.14$ ,  $SD = 2.79$ ), and 6 drivers were males ( $M_{age} = 29.17$ ,  $SD = 8.47$ ). In the experimental condition 4 drivers were females ( $M_{age} = 25.25$ ,  $SD = 2.06$ ) and 13 drivers were males ( $M_{age} = 35.08$ ,  $SD = 15.01$ ). A oneway ANOVA that contrasted age in the two groups was not significant:  $F(1, 28) = 2.34$ ,  $p = .13$ . Average years of driving experience were 8.15 ( $SD = 6.25$ ) in the control condition and 13.76 ( $SD = 13.91$ ) in the experimental condition. The difference between the two groups, tested with a one-way ANOVA, was not significant:  $F(1, 28) = 1.82$ ,  $p = .19$ . Average kilometres driven per year were 14,653 ( $SD = 10,957$ ) in the control condition and 10,147 ( $SD = 16,649$ ) in the experimental condition. The difference between the two groups was not significant:  $F(1, 28) = 0.71$ ,  $p = .40$ . All drivers had a standard Category-B driving licence. All participants had normal vision and none of them wore eyeglasses or contact lenses since they were incompatible with the eye-movement recording system. Participants were blind to the aims of the study and were told that they were involved in a research that tested an eye-movement recording equipment in night-time conditions. Participation was on a voluntary basis without any monetary reward.

### Design

The pedestrian crossing, previously tested also by Costa et al. (2020), was set up along Via del Triumvirato in Bologna along a straight segment of 653 m connecting a signalised intersection with a roundabout. The road was a single carriageway with two lanes. Lane width was 5.35 m for a total width of 10.7 m. Mean hourly traffic volume during the study (7–10 p.m.) was 510 ( $SD = 40.59$ ). V85 (85th percentile speed) was 43 km/h.

The pedestrian crossing was an integrated system composed by five elements (Costa et al. 2020):

- Movement sensor for the detection of pedestrians in the waiting zone near the curbside area (Figure 1). The sensor was preferred over the push-button because Carsten, Sherborne, and Rothengatter (Citation1998) have shown that a large number of people waiting to cross tends to not push the button.
- Backlit 'Yield here to pedestrians' sign, 60 × 60 cm;
- Orange beacons. One for each side and positioned directly above the 'Yield here to pedestrians' sign. Diameter was 10 cm. Flashing rate was 1 Hz with a 30% on and 70% off duty-cycle (Figure 1).
- Asymmetric enhanced LED lighting with dedicated luminaires, one for each side, positioned on a cylindrical pole with an elevation of 6 m. Light sources were LED lamps. The lighting level was 70 lx in case of no pedestrian (default state), with an increase to 120 lx when a pedestrian was detected by the sensor. Both measures were referred to horizontal

lighting measured at the centre of the crosswalk, with the sensor facing up at street level. Light colour temperature was 5700°K. Light beam distribution was asymmetric, inducing a positive contrast of the pedestrian (Figure 1). Street lighting outside the crosswalk area was performed with high-pressure sodium lamps with a lighting level of 16 lx at street level, directly under the lamp.

Photograph of the experimental pedestrian setting including LED strips on both curbsides, backlit pedestrian crossing signs with surmounted flashing orange beacons, and asymmetric enhanced LED lighting positioned at an elevation of 6 m.



Figure 1. Components of the experimental pedestrian crossing: LED strips on both curbsides of the zebra crossing; backlit pedestrian crossing signs with flashing orange beacons; dedicated lighting with increase of the lighting level when the sensor detected a pedestrian.

In the control condition only the enhanced lighting from 70 to 120 lx (Figure 2) was in operation, whereas in the experimental condition all devices were active in case a pedestrian was detected (Figure 3), as shown in Table 1. The experimental design was between participants, comparing a group in a control condition with a different group in the experimental condition.

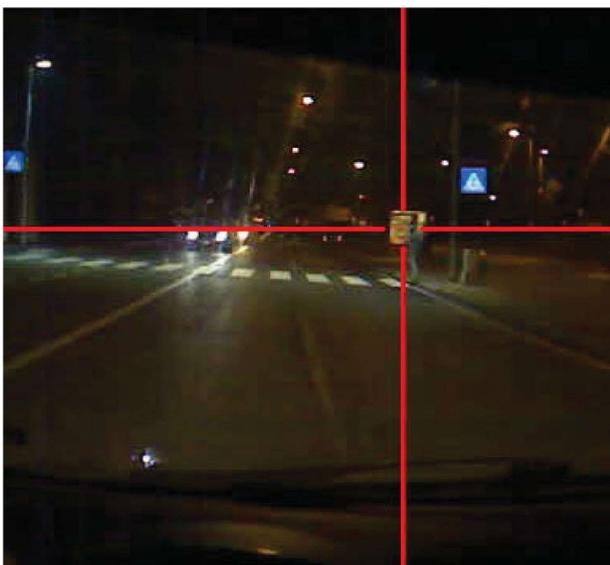


Figure 2. Driver's scene in the control condition. The red cross shows a driver's ocular fixation to the pedestrian.

### Procedure

Participants were told that the study was aimed at testing an eye-tracking device in night-time conditions and they were not informed about the presence of the experimental pedestrian crossing and the real aims of the study. In the control condition the pedestrian triggered only the enhancement of lighting level from 70 to 120 lx. The backlighting of the vertical signs was always active, while LED strips and orange beacons were switched off (Figure 2 and Table 1). In the experimental condition in-curb LED strips (steady mode) and backlit vertical signs were always active when the pedestrian was not present. When the pedestrian was detected the LED strips and the orange beacons started to flash (Figure 3), the backlit vertical sign remained switched on, and the luminaires increased lighting level from 70 to 120 lx. In both conditions only the left (northbound) carriageway was considered.

In both control and experimental conditions, the participant was requested to drive a round trip that started 513 m before the experimental pedestrian crossing, continuing for other 2214 m after the crosswalk, for a total of 2727 m (Figure 4). A research assistant was placed 60 m away from the crosswalk and warned the pedestrian about the incoming vehicle with an acoustic signal delivered on a two-way radio. Upon reception of the acoustic signal the pedestrian (a research assistant) moved to the waiting zone, triggering the sensor and entering with both feet just beyond the curb, at the beginning of the zebra crossing, gazing directly to the driver that was approaching without making any arm movement, using the same standardised procedure of Crowley-Koch, Van Houten, and Lim (2011). If the participant 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. The staged pedestrian was dark dressed (dark green, black or dark blue jacket and trousers).

Driver's eye movements were recorded with an ASL Mobile-Eye XG equipment. Sample rate was 30 Hz and angular precision 1. Vehicle kinematic data (speed, acceleration, GPS positioning), synchronised with a video recording of the driver's scene were recorded with a Video-VBOX-Pro. The ASL Mobile-Eye XG system returned a video with eye fixations and saccades superimposed to the driver's visual scene. Being the driver's visual scene recorded by both systems it was possible to synchronise eye movements with kinematic data offline.

The car was provided by the experimenters and was the same for all participants. At the beginning of the experiment the eye-tracking device was calibrated mapping eye movements to the driver's visual scene. The calibration was run in a parking lot, inside the car, with the car stopped. Participants were requested to sequentially fixate 20 specific points, vertexes and small objects in the visual scene. After calibration par-

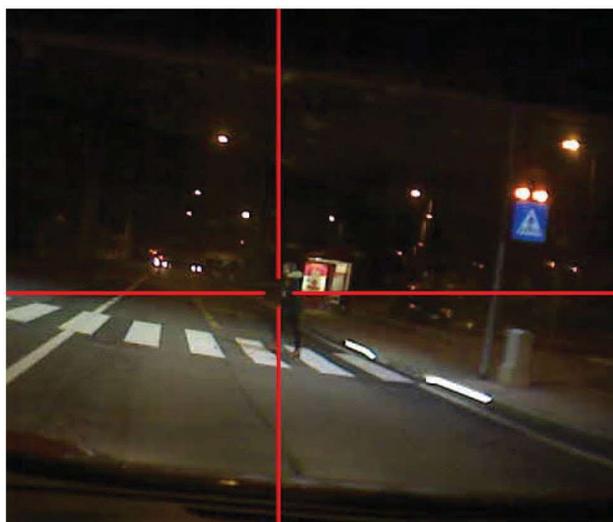


Figure 3. Driver's view of the crosswalk in the experimental condition with enhanced lighting, in-curb LED strips and orange beacons. The red cross shows the position of an ocular fixation near to the pedestrian.

Participants were allowed to drive inside the parking lot to familiarise with the car and the mobile eye-tracker. A researcher stayed on the back seat for all the session, having to supervise the eye-tracker and the Video-VBOX systems. He was instructed to intervene only for giving directions and assistance to the driver in case of problems or emergency. The participant was instructed to drive normally along the route following the directions of the researcher. At the end of the driving session the precision of the eye-tracker was newly tested, with the driver having to fixate 20 specific landmarks.

Each participant performed only one trial, either in the control or the experimental condition. The experience of the pedestrian in that specific crosswalk, in fact, could have primed the driver to pay more attention to potential pedestrians, driving more cautiously in additional trials.

Every care was assured that the pedestrian complied to the standard protocol in both conditions. The experimental sessions were run in four separate evenings from 6 to 10 p.m. with comparable traffic and weather conditions.

**Table 1.** Configuration of the pedestrian crossing in the control and experimental condition.

	Flashing LED strips	Flashing Beacons	Backlit vertical sign	Enhanced lighting from 70 to 120 lux
Control	Off	Off	On	On
Experimental	On	On	On	On



**Figure 4.** Route travelled by participants in the control and experimental condition, with indication of the crosswalk position.

## Data analysis

A session was dropped in case the participant was preceded at a short distance by another car or in case the pedestrian was too late in reaching the waiting zone. In the analysis of oculomotor behaviour, we considered a fixation the permanence of the foveal focus on a specific spatial region ( $<1^\circ$ ) for at least three frames (100 ms).

For each session the following parameters (dependent variables) were assessed: yielding compliance, pedestrian detection, distance of first fixation to the pedestrian area, total fixation time to the pedestrian area, standard deviation of horizontal eye movements, and slowing distance.

Yielding compliance and pedestrian detection between the two conditions were tested with a Chi-square test. A post-hoc power analysis was performed with GPower (Faul et al. 2007). Considering an effect size of 0.6, a total sample size of 30 participants, an alpha level of .05, and 1 degree of freedom, power ( $1 - \beta$ ) was .91.

All other parameters were tested with ANOVAs considering condition (control, experimental) as fixed factor and distance of first fixation, total fixation time to the pedestrian area, standard deviation of horizontal eye movements, and slowing distance as dependent variables. A post-hoc power analysis was performed with GPower (Faul et al. 2007). Considering an effect size of 0.6, a total sample of 30 participants distributed in two groups, an alpha level of .05, power ( $1 - \beta$ ) was .88.

## Results

### Yielding compliance

For each participant, a dichotomous variable recorded if the driver slowed down or stopped to allow the pedestrian to cross the road. Yielding compliance was 94.11% (16 out of 17 cases) in the experimental condition and 53.84% (8 out of 13 cases) in the control condition. The one-way Chi-square test that compared the two frequencies was significant:  $\chi^2(1, N = 30) = 4.61, p = .01, u = 0.39$ .



Figure 5. Regions of interest for the computation of fixations to the pedestrian areas.

### Pedestrian detection

The criterion for pedestrian detection was at least one fixation in the waiting zone of the crosswalk (Figure 5, left red frame). In the experimental condition the pedestrian was visually detected by the driver in the 100% of cases (17/17), whereas in the control condition the pedestrian was detected in the 92.3% of cases (12/13). The difference was not statistically significant:  $\chi^2(1, N = 30) = 0.02, p = .55$ .

### Distance of first fixation to the pedestrian area

Starting from 100 m from the crosswalk we determined if there was a fixation to the ROI of the waiting areas where the pedestrian appeared (Figure 5, left red frame). If a fixation was detected, using the synchronisation of the mobile eye-tracker with the kinematic data logger, we determined the distance of first fixation to the pedestrian area, using the same methodology as in Costa, Simone, et al. (2018). This parameter assessed how far the pedestrian was detected by the driver.

The mean distance of first fixation to the pedestrian area was 50.63 m (SD = 12.94) in the experimental condition and 36.01 m (SD = 17.58) in the control condition. The difference, tested with an ANOVA, was statistically significant:  $F(1, 14) = 4.77, p = .04, g^2_p = .25$ .

### Fixations to the pedestrian ROIs

This parameter was computed as summation of all the fixation times (ms) to the pedestrian area (Figure 5, left and right red frames), starting from 100 m until the instant in which the pedestrian started to cross. The phase of pedestrian crossing was excluded because of little interest since the driver simply followed with the eyes the pedestrian trajectory. In case the driver did not yield to the pedestrian we considered the fixations (if any) to the pedestrian ROIs in the interval 100 0 m.

The fixations were in mean for 1,577 ms (SD = 948) in the experimental condition and for 1,326 ms (SD = 1,086) in the control condition. The difference, tested with an ANOVA, was not significant:  $F(1, 20) = 1.59, p = .22$ .

### Standard deviation of horizontal eye movements

In case the driver yielded to the pedestrian we computed the standard deviation of x coordinates from 100 m to the point in which the pedestrian started to cross. In case the driver did not yield, the standard deviation of x coordinates was computed in the interval 100 0 m. This parameter assessed the dispersion of horizontal visual exploration of the scene. In case of high standard deviation, it could be suggested that the driver was more apt to detect a pedestrian in the peripheral field approaching the road. The standard deviation was expressed in angular degrees of the visual field.

The mean standard deviation was 5.96 (SD = 1.97) in the experimental condition and 3.88 (SD = 1.73) in the control condition. Main effect for condition was significant:  $F(1, 13) = 19.38, p = .001, g^2_p = .60$ .

### Slowing distance

This parameter was computed only in case the driver yielded to the pedestrian. It was computed examining speed and longitudinal acceleration from the kinematic data. Starting from 100 m we computed the distance from the crosswalk in which the driver started to slow down to yield to the pedestrian.

Slowing distance was assessed examining speed and distance data sampled by the Racelogic Video VBox system. The distance was computed as the difference in spatial positioning between the crosswalk and the first peak (acceleration

followed by deceleration) that preceded the crosswalk. This peak in the speed vs. space curve designated the point in which the driver started to slow down before the crosswalk.

The mean distance at which the driver started to slow down for giving way to the pedestrian was 67.69 m (SD = 14.80) in the experimental condition and 41.25 m (SD = 10.11) in the control condition. The difference, tested with an ANOVA, was significant:  $F(1, 12) = 15.22$ ,  $p = .002$ ,  $g^2_p = .56$ .

### Speed at 100m from the crosswalk

Mean speed at 100 m from the crosswalk was measured for controlling that this parameter was not critically different in the two conditions. Speed at 100 m was 45.83 km/h (SD = 6.58) in the experimental condition and 46.27 km/h (SD = 6.82) in the control condition. The difference, tested with an ANOVA, was not significant:  $F(1, 18) = 1.34$ ,  $p = .26$ .

### Discussion

In this study we tested the driving behaviour and visual attention of drivers approaching an experimental crosswalk that included enhanced lighting, flashing in-curb white LED strips, backlit vertical signs, and orange flashing beacons. These devices were activated when a pedestrian approached the crosswalk and were aimed to increase the crosswalk lighting level and the driver's attention to the crosswalk and the pedestrian. Specifically, in this study we tested the difference between a condition in which only enhanced lighting and backlit vertical signs were active (control condition), with a condition in which all the devices were active.

The integrated lighting-warning system that was under test in this study proved to significantly increase the crosswalk safety. The activation of the flashing devices strongly increased the yielding compliance (p40.27%) to 94.11%, a rate that is comparable to the use of pedestrian hybrid beacons (PHBs) and the use of rectangular rapid flashing beacons (RRFBs). PHBs are activated by pedestrians when needed and consists of two horizontally-arranged red lenses above a single yellow lens. When the pedestrian activates the system, the yellow beacon begins to flash, followed by a steady red signal indicating motorists need to come to a complete stop. In a third phase, the red beacons start alternating flashing, indicating to drivers that they can proceed once pedestrians are clear. In Arizona, where PHBs had been operating for multiple years, the driver compliance rate was 97% (Fitzpatrick et al. 2006; Stapleton et al. 2017). Drivers, however, must be educated about the meanings of the PHB states, which are not straightforward and selfexplaining. Furthermore, their installation costs are very high, and the system tends to convert an unsignalized crosswalk in a signalised crosswalk.

The yielding compliance recorded for the combination of in-curb LED strips and beacons is also comparable to that recorded for rectangular rapid flashing beacons (RRFBs) (Fitzpatrick et al. 2011; Shurbutt and Van Houten 2010, Stapleton et al. 2017), generally ranging from 72% to 100%. RRFBs have also the advantage of being relatively low-cost.

The activation of the two flashing devices induced the drivers to slow down earlier when yielding to the pedestrian (26.44 m). In the experimental condition the slowing down phase started in mean 68 m from the crosswalk, before the pedestrian activated the flashing devices at a distance of 60 m. This could be explained considering that in the experimental condition the in-curb LED strips were always switched on in steady mode, also if the pedestrian was not present. In case the pedestrian was present, the in-curb LED strips changed their status to flashing. The light from the LED strips could have alerted the drivers, prompting an earlier slowing down response in comparison to the control condition.

In the analysis of eye movements, we found that the pedestrian area was visually detected earlier in the experimental condition. The first fixation directed to the pedestrian area occurred at a mean distance of 50.63 m in the experimental condition and at a mean distance of 36.01 m in the control condition. Indeed, the activation of the flashing devices promoted a visual exploration of the pedestrian area 14.63 m in advance.

In an additional analysis we tested the difference in the two conditions for the standard deviation of horizontal eye movements. This measure assessed leftright exploration of the visual scene. A low standard deviation was an index of the driver looking straight ahead, limiting the saccades on the regions outside the road. With a high standard deviation,

the driver tended to avert more the gaze from the ahead direction to the peripheral field. When approaching a crosswalk, a higher standard deviation for horizontal eye movements could result in a safer behaviour since the driver better explored the peripheral areas, where a pedestrian could pop-out. In our case the mean standard deviation was significantly higher ( $p=53.75\%$ ) with the activation of the flashing devices.

We found no differences for the detection of the pedestrian in the two conditions. This could be explained by the fact that in both conditions the enhanced lighting level was active. This lighting extended also for 1 m in the pedestrian's waiting zone. Furthermore, the lighting system was with double asymmetry, creating a positive contrast between the pedestrian and the dark background, maximising pedestrian conspicuity. This could have facilitated the pedestrian detection also in the control condition. In addition, it should be considered that the participants, although blind to the aim of the study, were well aware of taking part to an experimentation in which some parameters linked to their visual behaviour and driving style was recorded. This could probably have induced a hyper-safe driving style in which attention to the road was enhanced in comparison to a default driving condition.

A main role in explaining the results of this study was played by the bottom-up attention capturing effect of flashing stimuli in the visual field. The attentional system tends to favour orienting to transients (Folk, Remington, and Johnston 1992), especially when stimuli have low contrast (Gerathewohl 1953). Previous research on the use of standard flashing beacons for increasing driver's yielding compliance found an effect of  $p=18\%$  (Mutabazi and Dindial 2007), considerably lower than the increase of  $p=40.27\%$  found in this study. This difference was probably due to the additional effect of in-curb LEDs. The effects are probably not due to the increased lightness level of the flashing LEDs because they were embedded in the curbs, in a direction perpendicular to the zebra crossing pavement. They had no influence on the pedestrian's waiting zone in the sidewalk. They could play a role in increasing the conspicuity of the pedestrian's legs and feet when crossing, but not during the waiting phase, to which all the measures considered in this study were referred to.

The study has some limitations due to the limited number of participants in the control and experimental conditions, to the fact that the innovative crosswalk design was tested only in one site, and to the 'novelty effect' induced by the flashing white LED in-curb strips that were new to drivers. It is possible that a repeated exposure to this device could result in a habituation that would decrease the effect of capturing the driver's attention. Further research is needed to test the effectiveness of the warning-lighting system in different road conditions and along an extended period of some months. Additionally, future research should clarify the effectiveness when the driver or the pedestrian have specific impairments.

The lighting colour of the in-curb LED strips was white. The reason was to combine the alerting flashing effect with an increased lighting of the zebra crossing. According to the EN-12352 'Traffic control equipment – Warning and safety light devices' (European Committee for Standardization 2006) the colours admitted for warning and safety light devices is yellow and red. Since the flashing devices are warning lights, the white flashing LEDs embedded in the curbsides could be incongruent with the driver's expectations about the standard colour of warning signs. A standard and coherent orange (amber) colour for both the beacons and the in-curb LED strips could enhance the legibility of the warning signs included in the crosswalk and the overall effectiveness of the lighting-warning system.

The experimental setup did not allow to ascertain the differential contribution of the in-curb LED strips or the orange beacons to the results, since they were both active in the experimental condition. A future investigation should better try to test the two devices separately. In a previous test of the integrated lighting-warning system we found that only the combination of the two flashing devices induced a significantly higher yielding compliance in comparison to a condition in which only enhanced lighting was active (Costa et al. 2020). In the previous study, however, only yielding compliance was measured in an ecological context in which no driver's eye movements were recorded. The enhanced lighting operated in two steps, increasing the lighting level of the crosswalk to 70 lx when no pedestrian was detected, and further increasing the level to 120 lx when a pedestrian was detected. When the pedestrian was present the illuminance level of the crosswalk was very high, probably reducing the effect of the flashing devices. Their effects, in fact, are attenuated whenever the contrast with the baseline lighting level is reduced.

In-curb LED strips have two main advantages: (i) they are in a more central position in the driver's visual field in comparison to the beacons, and therefore nearer to the foveal vision of a driver looking straight ahead to the road, and (ii) they are placed exactly where the pedestrian is expected to cross the road. Their disadvantage is that they are placed

very low, at 10 cm from the road pavement, and therefore they are less visible in the far distance. The beacons have the advantage of being placed high and the disadvantage of being placed more sideways. The higher the lateral clearance of a road sign and the higher is the adverse effect on sign vision and identification (Costa, Bonetti, et al. 2018).

The same EN-12352 (European Committee for Standardization 2006) regulates the continuity of emitted light in warning and safety light devices. Warning signs, according to this standards, could emit in a continuous (steady) light in class F1, with a rate between 55 and 75 flashes per minute in class F2, with a rate of 40–80 flashes per minute (class F3), and between 120 and 150 flashes per minute in class F4. In our case the flashing rate was 60 flashes per minute (1 Hz), with an on-time of 50% for the LED strips and an on-time of 30% for the beacons. Two parameters of the flashing pattern could have a significant impact on the driver's behaviour and attention: the flashing rate and its regularity. Specifically an increase in flashing rate or an increase in flashing irregularity or both could help in attracting more driver's attention, as showed by Shurbutt et al. (2009). Rectangular rapid flashing beacons, for example, are very effective in increasing yielding compliance to levels ranging from 72% to 94% (Fitzpatrick et al. 2011; Shurbutt and Van Houten 2010) and Stapleton et al. (2017) found a 100% yielding compliance when this device was tested. The incremental effect of flashing irregularity was tested by Van Houten, Ellis, and Marmolejo (2008) who evaluated the installation of amber LED flashers with an irregular flash pattern on motorists' yielding rate. The irregular LED flashers produced a marked increase in yielding behaviour. Therefore, it could be suggested that the implementation of an irregular or rapid flashing pattern in the in-curb LED strips or in the beacons or in both would further increase the effectiveness of the lighting-warning system that was tested in this study.

LED technology has greatly developed in the last decade, and we still have to completely exploit the potential impact of this technology in the field of traffic safety. In this study we tested the use of LED strips embedded in zebra-crossing curbs for capturing the driver's attention to pedestrians in night-time condition. Following this line, LED strips, either steady or flashing, could be used to delimit and surround obstacles on the carriageway, alert about dangerous spots, or guiding the driver along highway exits, critical curves and intersections, increasing road safety in a multitude of conditions.

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## Disclosure statement

No potential conflict of interest was reported by the author(s).

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