Do detection-based warning strategies improve vehicle yielding behavior at uncontrolled midblock crosswalks?

Qinaat Hussain [a,*], Wael K.M. Alhajyaseen [a,*], Ali Pirdavani [b,c], Kris Brijs [c], Khaled Shaaban [d], Tom Brijs [c]

[a] Qatar University – Qatar Transportation and Traffic Safety Center, College of Engineering, PO Box 2713, Doha, Qatar
[b] UHasselt, Faculty of Engineering Technology, Agoralaan, 3590 Diepenbeek, Belgium
[c] UHasselt, Transportation Research Institute (IMOB), Agoralaan, 3590 Diepenbeek, Belgium
[d] Utah Valley University, Department of Engineering, 800 W University Pkwy, Orem, UT, USA

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ABSTRACT

Pedestrians being the most vulnerable road users account for a large proportion of injuries and fatalities from road traffic crashes. Pedestrians are involved in around one-third of the whole fatalities coming from the road traffic crashes in the state of Qatar. In areas with uncontrolled midblock crosswalks, it is very crucial to improve drivers' alertness and yielding behavior. The objective of this driving simulator study is to investigate the impact of pedestrian detection strategies and pavement markings on driving behavior at high-speed uncontrolled crosswalks. To this end, an untreated condition (i.e. Control) was compared with three treatment conditions. The three treated conditions included two detection strategies, i.e., advance variable message sign (VMS) and LED lights, and road markings with pedestrian encircled. Each condition was tested with a yield/stop controlled marked crosswalk for two situations, i.e. with vs. without a pedestrian present. The experiment was conducted using the driving simulator at Qatar University. In total, 67 volunteers possessing a valid Qatari driving license participated in the study. Different analyses were conducted on vehicle-pedestrian interactions, driving speed, variations in acceleration/deceleration and lateral position. The results showed that both the LED and VMS conditions were helpful in increasing yielding rates up to 98.4 % and reducing the vehicle-pedestrian conflicts significantly. Furthermore, both treatments were effective in motivating drivers to reduce vehicle speed in advance. Considering the findings of this study, we recommend LED and VMS conditions as potentially effective solutions to improve safety at yield/stop controlled crosswalks.

1. Introduction

Pedestrian constitute a large proportion of fatalities and injuries coming from road traffic crashes, i.e., every year around 40,000 pedestrians are killed on the roads worldwide (Naci et al., 2009). Therefore, they are considered as the most vulnerable group in traffic. Crossing the road at uncontrolled mid-block crosswalks is a hazardous condition for pedestrians and can lead to a crash. One of the main reasons of crashes at these locations is that drivers do not yield to pedestrians. The risk is higher in developing countries where speeds are high, many pedestrians are seen on roads, and aggressive driving exists. The most common method of addressing this problem is to install a traffic signal at uncontrolled midblock crossings. Nevertheless, this method is not feasible at all crossings due to the expensive cost of installation and maintenance, especially for developing countries. Moreover, signalized mid-block crossings may lead to travel delay, extra fuel consumption, and air pollution. Therefore, it is not uncommon to find high-speed uncontrolled crosswalks in developing countries. In addition to traffic signals, various types of solutions have been implemented to improve traffic safety at uncontrolled mid-block crosswalks, such as physical treatments (e.g. raised pedestrian crosswalks, speed humps, built environment, chicane), auditory road markings (e.g. transverse rumble strips), pavement markings (e.g. parallelogram-shaped markings), and intelligent transport system based treatments (e.g. in-vehicle warning system, rapid flash beacons).

In the state of Qatar, pedestrians are involved in almost one-third of

the overall fatalities arising out of road traffic crashes (QNTSC, 2013). The main contributory risk factor in such crashes is the travelling speed that influences not only the probability of a crash but also its severity (Aarts and van Schagen, 2006; Alhajyaseen, 2015; Heydari et al., 2014; Hussain et al., 2019a). According to White and Caird (2010), situations where a driver fails to yield for a pedestrian may arise when a driver does not expect pedestrians at crosswalks, due to distraction or due to lower visibility (Alhajyaseen et al., 2013). In general, pedestrians approaching the un-signalized marked crosswalk have priority over vehicles to cross. However, most of the drivers do not yield to pedestrians at mid-block crosswalks (Shaaban et al., 2017). On the other hand, extreme weather conditions (e.g., hot weather during the summer season in Qatar) and the multi-cultural backgrounds of pedestrians could contribute to illegal crossing (Li and Fernie, 2010; Shaaban et al., 2018). This could lead to severe conflicts between pedestrians and vehicles. In places with uncontrolled midblock crosswalks, intensive pedestrian traffic, and higher posted speed limits, it is essential to improve drivers' alertness and to motivate them to reduce their travelling speed while approaching pedestrian crosswalks.

Traditionally, pedestrian safety has been assessed by crash data. The historical crash data can be analyzed through statistical models to estimate the effect of different contributing factors on pedestrian safety, such as, the effects of road design elements, climate change, weather, visibility (day vs night) etc. on pedestrian safety. However, crashes are rare and complex events with limited information on behavioral and situational aspects (Svensson and Hydén, 2006), which makes it difficult to draw conclusions on the preventive measures. In contrast, pedestrian safety can be explored using vehicle-pedestrian conflicts through surrogate safety measures (Alhajyaseen et al., 2012; Chen et al., 2017). The term "surrogate safety measures" can be defined as the methods that are used to quantify traffic conflict events, which can be observed directly and more frequently than crashes (Johnsson et al., 2021; Lord et al., 2021). These measures can be used to predict conflicts and near-crash events (Alhajyaseen and Iryo-Asano, 2017; Chen et al., 2017; Hydén, 1987; Iryo-Asano and Alhajyaseen, 2017; Varhelyi, 1998). Ni et al. (2016) analyzed the conflicts considering three interaction patterns, i.e., hard interaction, no interaction, and soft interaction, identified based on speed profiles and conflict indicators. Gang et al. (2012) proposed a model to evaluate the degree of risk using a clustering algorithm based on the fuzzy cluster analysis method. Three traffic conflict indicators, namely, Time-To-Collision (TTC), Post-Encroachment Time (PET), and Deceleration to Safety Time (DST), were also considered in this model. In cases where crossing trajectories are involved between pedestrians and vehicles, it is possible to measure critical events by means of post encroachment time (PET), as it considers the exact difference in time between a pedestrian leaving the conflict area and a conflicting vehicle entering the same area (Archer, 2005).

2. Literature review

The impact of rectangular rapid flash beacons on pedestrian safety has been evaluated in several studies (Frederick and Van Houten, 2008; Porter et al., 2016; Ross et al., 2011; Shurbutt and Van Houten, 2010; Shurbutt et al., 2009). All studies reported that these beacons could improve drivers' yielding rates at midblock crosswalks. The rectangular flashing light is installed under the static pedestrian sign, which operates through a push-button system. The system does not offer any additional instruction to drivers, just a flashing light under the roadside pedestrian sign.

Patella et al. (2020) assessed the effectiveness of an LED lighting crosswalk in terms of drivers' traveling speed in Rome, Italy. White illuminated LED stripes were used in nighttime conditions and were tested for two different situations, i.e., pedestrian present vs pedestrian absent. The speed data was collected for 400 observations in two situations (i.e., 200 with no pedestrian present while 200 with a pedestrian (s) present) using a Telelaser instrument. The results showed that the

mean traveling speed was reduced by around 7.8 km/h in both situations.

Another study tested a VMS replicating the default pedestrian crosswalk static sign on a Swedish road in an observational study (Baghdarusefi, 2009). The performance of VMS was evaluated through both the drivers' traveling speed and yielding rates. Results revealed that drivers' traveling speed was reduced together with improved yielding rate, when the VMS was active.

Guo et al. (2016) evaluated the impact of parallelogram-shaped road markings on traveling speed and crashes at midblock crosswalks in urban roads with a speed limit of 60 km/h in observational cross-sectional studies. The parallelogram-shaped road markings were installed on approaches to unsignalized crosswalks. The length of the markings in their study ranged from 60 m to 70 m. The study reported a mean speed reduction of 3.79 km/h ranging from 1.89 to 4.41 km/h. Furthermore, based on their crash models, the pavement markings were helpful in reducing crash rate by 24.87 %. This study also presented the effectiveness of pavement markings, only in terms of speed, but no further evaluation of vehicle-pedestrian interactions was addressed.

Gómez et al. (2011) investigated the effectiveness of advanced yield markings together with a prompt sign indicating "yield here to pedestrian" in terms of crash/near crash events in a driving simulator. The markings were used on approach to unsignalized midblock crosswalks. Twenty-four subjects participated in the experiment. Results showed that the pavement markings together with a prompt sign helped in reducing the number of crash/near crash events for different situations.

In an observational before-after study, Liu et al. (2011) tested transverse rumble strips to reduce crashes and drivers' traveling speed at pedestrian crosswalks in China. The vehicle speed data from 12 different sites on rural roads containing speed limits of 60 and 80 km/h was collected. The results showed that on average 9.2 km/h and 11.9 km/h speed reduction was observed on roads with speed limits of 60 and 80 km/h, respectively. In addition, the authors reported that transverse rumble strips could also reduce expected crash frequency at pedestrian crosswalks by 25 %.

In the case of roads with posted speed limits higher than 50 km/h, physical measures such as build-outs, speed humps, and chicanes would not be feasible solutions to choose. In such a case, non-physical warning or nudging measures such as road markings with different colors or patterns, in-vehicle warning system, flashing lights on road surface or roadside visual animation shown on VMS could be effective and feasible tools to improve pedestrian safety (Baghdarusefi, 2009; Gómez et al., 2011; Nambisan et al., 2009; Patella et al., 2020). Such measures can be used to produced visual or auditory nudges to increase drivers' attention level and to influence their choice of a certain behavior (Köhler et al., 2019).

In sum, different treatments have been implemented at unsignalized crosswalks, either in real or simulated environments. Most of the studies in the literature used rectangular rapid flash beacons with a flashing light installed under the static sign, which is operated through a push-button system. Only few studies can be found that have used detection-based strategies, either white LED light units installed at crosswalks during nighttime (Patella et al., 2020) or a VMS replicating the default pedestrian crosswalk static sign (Baghdarusefi, 2009). To improve pedestrian visibility at crosswalks during nighttime conditions, vertical road lighting systems have also been studied (Gibbons and Hankey, 2006; Marchant et al., 2020; Saraiji, 2009; Saraiji and Oommen, 2015). Moreover, impacts of various types of pavement markings have also been evaluated in many studies. Interestingly, previous studies have focused on single parameters such as yielding behavior or speed reduction. To the best of our knowledge, the effect of treatments on a combination of different parameters has not yet been investigated. Furthermore, although the effectiveness of VMS at pedestrian crosswalk has been studied by a study (Baghdarusefi, 2009), animation-based VMS have not been examined before. In this paper, we address these gaps in the literature by investigating the impacts of different non-physical

measures on drivers' traveling speed, variations in acceleration/deceleration, vehicle-pedestrian interactions (i.e. yielding rates and PET values), and lateral position altogether. In addition, to the best of our knowledge, studies that investigate these issues in Qatar, have not been found in the literature. The state of Qatar is a unique case in terms of the diverse driving population (Soliman et al., 2018; Timmermans et al., 2019). In this regard, previous research indicates that heterogeneous driving populations with many different origins could contribute to the acceptance of risk-taking behavior (Timmermans et al., 2020). In addition, this factor could also induce different driving behavior among drivers, for instance, drivers' traveling speed and acceleration maneuvers (Almallah et al., 2020; Hussain et al., 2019b). Therefore, the results from this study may reveal interesting findings on vehicle-pedestrian interactions.

3. Study objectives

The main objective of this driving simulator study is to investigate the effectiveness of pedestrian detection and road marking strategies at high-speed uncontrolled crosswalks in the State of Qatar. In this regard, we tested four different conditions, i.e., two detection strategies (LED pavement lights and VMS), which were compared with pedestrian encircled pavement markings, and an untreated control condition. The four conditions were tested for two different situations, i.e., pedestrian absent (PA) and pedestrian present (PP). The detection-based strategies were designed in a way to detect pedestrians upon their arrival at the crosswalks and then warn the drivers by providing particular visual clues (i.e., warning message displayed on the VMS panel and flashing red LED light units). In this study, we provide new insights on flashing lights by introducing LED flashing ground lights in front of the drivers instead of roadside flash beacon. This was done because the roadside objects are not sufficiently noticed by drivers (Costa et al., 2014), and LED ground lights fall in the direct field of drivers and could increase drivers' alertness (Köhler et al., 2019).

The main objective can further be divided into three sub-objectives: (1) to test whether the countermeasures improve the vehicle-pedestrian interactions by increasing yielding rates and reducing conflicts at the uncontrolled crosswalks; (2) to investigate if the countermeasures influence drivers' traveling speed; (3) to evaluate drivers' lateral position which is an important safety indicator and could be influenced due to the additional elements (e.g. roadside objects) on the road (Bella, 2013).

4. Methods

4.1. Simulation apparatus

The experiment was conducted using a driving simulator at Qatar University (see Fig. 1), previously validated for objective and subjective validities (Hussain et al., 2019c) as well as for the geometric field of view (Hussain et al., 2020a). The simulator consists of two main components:

Fig. 1. Range Rove Evoque- A driving simulator located at Qatar University.

the first component is the driving unit, which is a fixed-base Range Rover Evoque cockpit equipped with all tools and functions provided in the real car, such as an automatic gearbox, pedals, speedometer, indicators, and a force-feedback steering wheel. The second component is composed of three LCD screens, each of 65-inch (165.1 cm) screen size while dimensions of 90.1cm × 145.3cm. The system provides a field of view of 135° with high resolution of 5760 × 1080 pixels and refresh rate of 60 Hz. The components are integrated with STISIM Drive 3, which is a product of Systems Technology, Incorporated (STI) and CalPot32 software, which offer high-speed sound processing and graphics (Eriksson et al., 2018). The system is capable of producing proper engine and road noise, which is transmitted through the simulation auditory system. More than 67 driving parameters such as speed, longitudinal/lateral position, longitudinal/lateral acceleration, pedal inputs, and reaction time etc. can be collected using this driving simulator.

4.2. Participants

In this study, sixty-seven volunteers were recruited with as a minimum requirement, being in possession of a valid type B Qatari driving license that permits of driving any type of passenger cars. To reduce the risk of simulation sickness, each participant was informed beforehand to avoid any kind of food or drink (except for water), at least two hours prior to the test (Kennedy et al., 1993). Regardless of the given instructions, three of the participants were affected due to simulation sickness and were removed from the analyses. Therefore, data from 64 participants was use for analyses. Regarding gender of the participants, 48 were male and 16 were female drivers. The participants were from 20 different nationalities of whom 31 were Arabs. Age of the participants ranged from 19 to 58 years with a mean age of 28.89 years (SD: 7.3 years). Mean driving experience was 8.45 years, ranging from 1 to 30 years (SD: 6.3 years). Regarding annual mileage, 45.3 % drove more than 20,000 km, 31.3 % drove 10,000–20-000 km, and 23.4 % drove less than 10,000 km per annum.

4.3. Simulation drives

The study adopted a 4 × 2 within-subject factorial design with four conditions, i.e., control condition, pedestrian encircled pavement markings (Marking), flashing LED light units (LED) and variable message sign (VMS), presented to the drivers in two different situations (i.e. pedestrian absent PA and pedestrian present PP). This implies that every subject was exposed to 8 crosswalk events, i.e., 4 conditions x 2 situations. For creating variation in the simulation drives and for reducing the probability of drivers' learning effects, crosswalks were connected with various filler pieces such as dummy pedestrian crosswalks, signalized intersections, and different maneuvers by front vehicles. Two simulation drives (each of approximately 12 km long) were designed to replicate the exact environment and road layout of the urban/suburban road in the city of Doha with a posted speed limit of 80 km/h. This was done to reduce the risk of simulation sickness and to provide the participants with an opportunity for a break in between the simulation drives. The road geometry was three lanes in each direction with a lane width of 3.65 m. These conditions replicate a high-speed uncontrolled crosswalk in the city of Doha, Qatar (see Fig. 2).

The eight crosswalk events to be analyzed were designed along the two simulation drives (4 crosswalk events per drive) in a way to include equal distributions of conditions and situations in each simulation drive (2 with Situation PA while 2 with Situation PP). The crosswalk events in the first simulation drive were sequenced as a) Markings – Situation PA; b) VMS – Situation PP; c) LED – Situation PA; and d) Control – Situation PP. Meanwhile, the sequence of the crosswalk events in the second simulation drive was a) LED – Situation PP; b) Control – Situation PA; c) VMS – Situation PA; and d) Markings – Situation PP. The sequence of the crosswalk events in both simulation drives were then fixed for all the participants. However, each participant completed these two simulation

Fig. 2. A high-speed uncontrolled crosswalk in the city of Doha.

drives in a random order. Video footages and Google Earth images were used to replicate the exact road environment. This was done to improve the sense of presence and reduce the risk of simulation sickness in the experiment (Almallah et al., 2021). In addition, according to Bella (2005, 2008), this could also improve the realism of the simulated environment. SketchUp Pro (version 18.0.16975) was used to design roadside elements, e.g., buildings, roadside signs and streetlights etc. Moreover, in terms of traffic composition, the simulation scenarios included 47.8 % of sedan cars, 45.7 % SUV, and 6.5 % trucks, vans and buses, which replicates the real-world situation in the city of Doha.

4.4. Treatment conditions

In total, eight marked crosswalks were designed for both targeted situations (i.e. PA situation and PP situation). In the PA situation, the crosswalks were designed without any pedestrian while in the PP situation a pedestrian was approaching the crosswalk at a constant speed of around 5 km/h (Muley et al., 2018). The pedestrian located 6.5 m away from the right edge of the road was triggered in a way to start walking when the distance between the participant's car and the pedestrian was 150 m. The triggered setting was based on the speed limit and the pedestrian walking speed to ensure pedestrian arrival at the marked crosswalk on the participant's vehicle approach. However, vehicles traveling with higher speed or driving on the second or inner most lane could pass the pedestrians without yielding for them. The control condition was a marked crosswalk with a stop-line placed at 5 m distance before the crosswalk and combined with the default static signs but without any additional treatment. The same crosswalk setting and default static signs were also used in all other treatment conditions.

4.4.1. Pedestrian encircled pavement markings

In this condition, white circular pavement markings were placed on each lane. The markings were installed prior to the crosswalk and pictured an encircled Qatari pedestrian symbol. These markings were repeated three times with an interspace of 30 m (see Fig. 3). The first set of markings was located 30 m before the marked crosswalk.

Fig. 3. Pedestrian encircled pavement markings.

4.4.2. Flashing LED light units (LED)

In this condition, dynamic LED ground lights were installed on the road surface on a stop-line, 5 m prior to the crosswalk. In case there is no pedestrian present, yellow LED lights flash at a frequency of 2 HZ (Fig. 4a) (Masuda et al., 2015). In the PP situation, these yellow LED lights turn into red lights flashing at the same frequency of 2 HZ (Fig. 4b).

4.4.3. Variable message sign (VMS)

In this condition, the static sign was replaced with an advanced VMS, which was installed next to the stop-line on the right side of the road. The VMS displays a warning message in bilingual text (i.e. both in Arabic and English), together with a dynamic graphical warning. In the PA situation, the VMS instructs to slow down both in Arabic and English with a graphical representation of the crosswalk placed above the text (Fig. 5a). In addition, yellow lights in all corners of the panel flash at a frequency of 1 HZ. The content of the VMS changes in case a pedestrian arrives at the crosswalk. The text changes to "STOP" written both in Arabic and English, while the graphic changes into a crosswalk with walking pedestrians (Fig. 5b). Furthermore, red lights in all corners flash at the same frequency of 1 HZ. Finally, for one second, the red lights in the corners turn off, and the strips of the crosswalk change from white to red one by one, from right to left for a time period of 0.11 s.

4.5. Experimental procedure

Ethical approval for this study was obtained from Qatar University's Institutional Review Board (QU-IRB). Participants were recruited by means of official emails to the Qatar University community and announcements on different social media. All subjects registered in the experiment through an official registration website (www.qatardrivingsimulator.com). Participants were asked to sign an informed consent form upon their arrival to the simulation lab. After that, they were asked to fill in a pre-test questionnaire probing for socio-demographic information and driving-related questions using an online platform, i.e. 'Qualtrics'. Next, participants were given about 10 min practice drive to make sure that they get familiarized with the driving simulator. At the start of the test drives, participants were instructed to drive as they would normally do in real-world situations and to behave towards traffic rules as they would do in reality. Furthermore, they were informed they could quit the experiment anytime and for any reason. Each participant then completed the two simulation drives in random orders with a short break in between. Each simulation drive took about 15 min. Finally, participants answered a post-test questionnaire to obtain feedback on their experience of using the driving simulator and the treatments implemented in the experiment. The questionnaire took around 5 min to be completed. In total, the experimental session lasted for about one hour.

4.6. Data analysis

Data was collected for several variables (i.e., longitudinal distance, elapsed time, speed, acceleration, and lateral/longitudinal position) in ". DAT" format using STISIM Drive® 3. To analyze yielding rates, descriptive statistics were applied to summarize the differences. In addition, to analyze if the differences in yielding rates between the control condition and the test conditions were significant, three separate McNemar tests were conducted for each pairwise comparison. Based on the pedestrian and vehicle trajectories, PET values were calculated for each case where a participant yielded. In this regard, PET values were calculated as the temporal difference on a common specific spatial point on the crosswalk between the moment when the pedestrian left that reference point, and the moment when the vehicle's front-left corner arrived at it. Boxplots and t-tests (two-tailed/paired) were utilized to check whether differences were statistically significant. Moreover, for analyzing speed, acceleration/deceleration and lateral positions
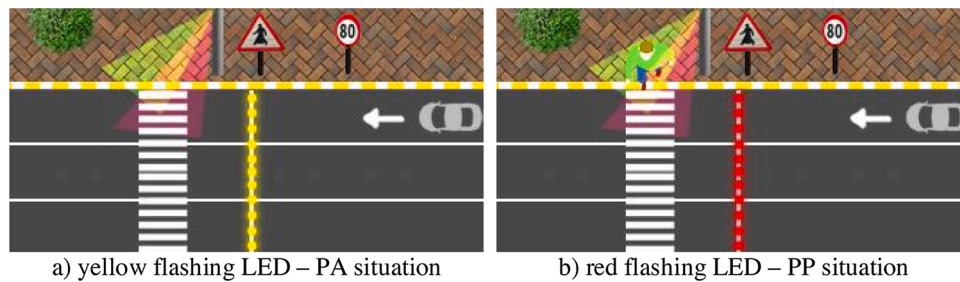
a) yellow flashing LED – PA situation   b) red flashing LED – PP situation

Fig. 4. Dynamic LED ground lights.

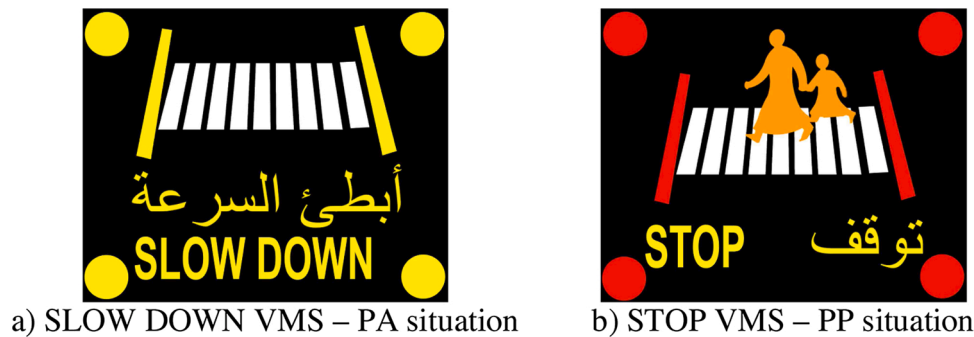a) SLOW DOWN VMS – PA situation   b) STOP VMS – PP situation

Fig. 5. Variable Message Sign (VMS).

analysis of variance (ANOVA) with repeated measures was used.

The scenario sections included for analysis in this study were all 300 m long, i.e. 200 m before and 100 m after the crosswalk. For the analysis of speed and lateral position, a point-based interpolation technique was used to extract individual speed on 7 points, each of these data points at an interdistance of 50 m. For the analysis of acceleration/deceleration, a zonal-based interpolation was adopted with extraction of standard deviation of acceleration/deceleration (SDAD) in 6 zones, each of these covering a total length of 50 m. SDAD was calculated to allow observation of variations in drivers' stopping behavior.

Within-subject repeated ANOVA tests were conducted separately for each of the variables of interest, i.e. 'speed', 'lateral position' and 'SDAD'. The independent variables for the ANOVA models were Situation (i.e. PA situation and PP situation), Condition (i.e. Control, Marking, LED, VMS), and Point (7) / Zone (6). This means that all the variables (i.e., Situation, Condition and Point/Zone) were repeated for all the participants in each ANOVA test. Previous studies with comparable sample size applied this data analysis technique to estimate differences between experimental conditions (e.g. Ariën et al., 2013; Calvi, 2018; Charlton et al., 2018; Hussain et al., 2018; Reinolsmann et al., 2019). Furthermore, pairwise comparisons adjusted by Bonferroni and t-tests (two-tailed/paired) were conducted to investigate differences in more detail. To conduct the ANOVA followed by pairwise comparisons (Bonferroni adjusted), IBM SPSS Statistics Version 26 was used. The ANOVA tests were conducted as repeated measures under General Linear Model.

Furthermore, subjective assessments were done through rating on a 5-point Likert scale and ranking of all conditions. To see if there was any causal linkage between demographic/contextual factors with the obtained rating/ranking for each treatment, Spearman's correlations were applied. Spearman's correlation was used since our variables of interests (rating/ranking) were in ordinal forms and since it does not require the assumption of normality (Hauke and Kossowski, 2011). The demographic/contextual factors included "gender" (0=female, 1=male), "age" (continuous variable), "ethnicity" (0 = non-Arab, 1=Arab), experience in years (continuous variable), and the average distance travelled per year (1 = 0–4,999 km; 2 = 5,000–9,999 km; 3 = 10,

000–14,999 km; 4 = 15,000–19,999 km; 5 = 20,000–25,000 km; 6 = >25,000 km).

In total, there were 160 cases or 'observations' per participants, i.e., 56 (7 points x 4 conditions x 2 situations) for the analysis of speed and lateral position, and 48 observations (6 zones x 4 conditions x 2 situations) for the analysis of SDAD. Participants were identified as outlier in case their values were at 1.5 interquartile range from the group's mean in more than 15 % of the total cases (15 % of 160 = 24 cases) (Ariën et al., 2013; Hussain et al., 2020b). In this regard, two participants were identified as outliers, therefore, their data was excluded from the statistical analyses. Thus, data from 62 participants were used for the analyses. However, for Section 5.6 "Subjective assessment of the tested conditions", the data collection through post experiment questionnaires for two participants was missing in the database. Therefore, the analysis on subjective assessment was done for 60 participants.

5. Results

5.1. Driver yielding rates

Fig. 6 shows the percentage of drivers that yielded at the crosswalk in
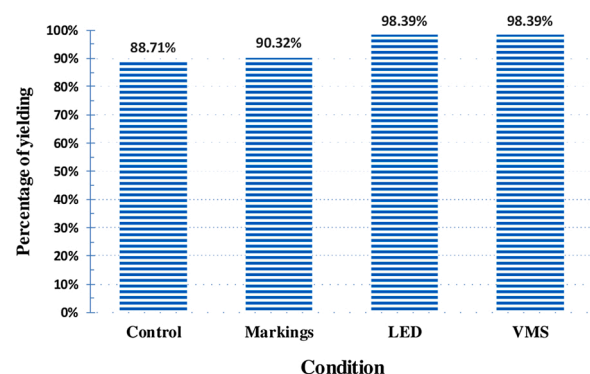

Fig. 6. Percentage of yielding in each scenario in PP situation.

each of the four conditions with a pedestrian present. It can be seen that even though a pedestrian was entering the crosswalk, 11.3 % of the drivers did not give priority and refrained from yielding in the control condition, followed by the condition with pavement markings (9.0 % of drivers not yielding). Yielding rate was higher in the other two conditions i.e. LED lights and VMS: in both conditions, 98.39 % of the drivers yielded to pedestrians. Interestingly, three drivers who not yielded in both control and marking conditions, did yield in the condition with LED lights, of which two drivers also yielded in the VMS condition. The McNemar tests determined that the yielding rate in the LED condition was significantly higher than the control condition at 0.05 significance level (p = .041). In addition, yielding rate in the VMS condition was higher than the control condition at 0.1 significance level (p = .077). However, there was no significant difference in the yielding rates between the control and Markings conditions (p = .999).

5.2. Vehicle-pedestrian conflicts

Fig. 7 illustrates the boxplots for PET together with individual values for PET for each of the four conditions. Dashed and solid horizontal lines represent the threshold values for PET for serious conflicts (i.e. less than or equal to 1 s) and slight conflicts (i.e. between 1 s and 3 s), respectively (Almodfer et al., 2016). It can be seen that both detection-based strategies (i.e. LED and VMS) eliminated all serious vehicle-pedestrian conflicts, while they reduced the slight conflicts. To investigate if the differences between the control condition and the test conditions were significant, separate t-test analysis (two-tailed; paired) was conducted. The analysis did not include negative PET values, i.e., cases where participants did not yield to pedestrians (7 in the control; 6 in the Marking; 1 in the VMS; and 1 in the LED conditions). The results showed that compared to the control condition (μ = 3.37 s), PET values significantly increased for the LED (N = 54; μ = 5.46 s; p < .001) and VMS (N = 55; μ = 5.52 s; p < .001) conditions. Different from that, the PET value was not significantly different in the condition with pavement markings (N = 52; μ = 3.27 s; p = .437).

5.3. Vehicle speed

Table 1 presents the results of the ANOVA tests (Greenhous-Geisser) for the analysis of speed. Results showed a significant main effect for the factors 'Condition' ($F_{(2,140)}$ = 13.2, p < .001), 'Point' ($F_{(3,159)}$ = 367.9, p < .001), and 'Situation' ($F_{(1,61)}$ = 231.7, p < .001). This implies that independent of any other factor, drivers' traveling speed was significantly different between the tested conditions, at different locations along the analyzed segments (7 points), and between both situational contexts (i.e. with vs. without pedestrian presence). Furthermore, the two-way interaction effects for 'Condition x Point' ($F_{(8,472)}$ = 24.1, p < .001) and 'Point x Situation' ($F_{(3,181)}$ = 258.4, p < .001) were also significant, meaning that traveling speed was significantly different

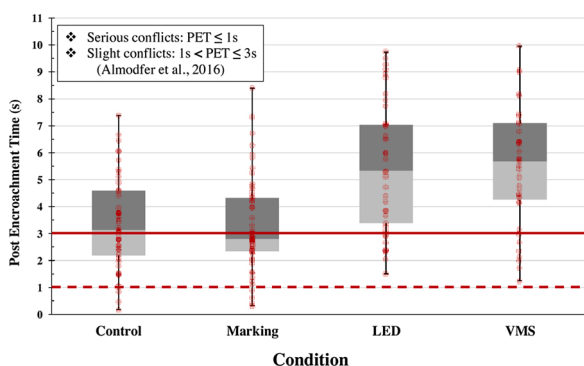**Table 1**

Analysis of speed: within-subject ANOVA test (Greenhouse-Geisser). (Bold p-values are significant at 0.05 significance level).

Effect	F	Dfs	p
Condition	13.2	2, 140	**<.001**
Point	367.9	3, 159	**<.001**
Situation	231.7	1, 61	**<.001**
Condition x Point	24.1	8, 472	**<.001**
Condition x Situation	1.5	2, 110	.227
Point x Situation	258.4	3, 181	**<.001**
Condition x Point x Situation	17.4	8, 466	**<.001**

between the tested conditions and situations along the analysis segment. In addition, the three-way interaction effect for 'Condition x Point x Situation' was also significant ($F_{(8,466)}$ = 17.4, p < .001), indicating that vehicle speed was significantly different between the tested conditions along the analysis segment and taken separately for each of the two situational contexts.

Further descriptive statistics and pairwise comparisons of the tested conditions are presented separately for the two situational contexts in Table 2. The pairwise comparisons of the tested conditions were conducted with Bonferroni adjustment for each situation separately. Compared to the control condition, the overall mean speed along the 300 m analysis segment (i.e. 200 m before and 100 m after the stop-line) significantly decreased only in the conditions with a detection-based format (i.e. LED and VMS), while there was no significant difference between the control and the Marking conditions. However, in the second situation where a pedestrian was present at the crosswalk, the mean speed significantly dropped only in the VMS condition. However, compared to the Marking condition, the mean speed significantly reduced in the detection-based treatments in the PP situation.

Fig. 8(a) and (b) visualize the plots for mean speed for all four conditions over the analysis section for the PA and PP situations, respectively. Compared to the other two conditions, the LED and VMS conditions stimulated participants to substantially reduce their traveling speed, and to do so sooner (i.e. further in advance) in both situations. Compared to the control condition, the maximum mean speed reduction at the stop-line was observed in the VMS condition (dμ = 11.5 km/h) followed by the LED condition (dμ = 10.7 km/h) in the PA situation (see Fig. 8a). In the PP situation, the maximum mean speed reduction was observed in the LED condition (dμ = 28.4 km/h) followed by the VMS condition (dμ = 27.3 km/h).

In Fig. 9(a–d), the red outlined boxes represent the areas (with respect to the stop-line) where most of the drivers initiated speed reduction for the situation where a pedestrian was present. Most drivers started decelerating well before the stop-line in the LED and VMS conditions (i.e. −120 to −60 m) when compared with the control (i.e. −80 to −30 m) and marking (i.e. −100 to −40 m) conditions. Moreover, the vertical gray line represents the location of stop-line. Interestingly, all participants stopped before the stop-line (the vertical grey bar) in the

Fig. 7. Boxplots and individual values for Post-Encroachment Time in PP situation.

Table 2

Descriptive statistics – mean speed; and pairwise comparisons. (Bold p-values are significant at 0.05 significance level).

| Condition	Control	Markings	LED	VMS
Mean speed (km/h) – Situation PA	80.5	76.9	73.9	72.8
Mean speed (km/h) – Situation PP	66.6	67.9	63.8	61.6
Pairwise comparisons (p-values) – Situation PA				
Control	1	.223	**<.001**	**<.001**
Markings		1	.084	**.027**
LED			1	>.999
VMS				1
Pairwise comparisons (p-values) – Situation PP				
Control	1	>.999	.051	**<.001**
Markings		1	**.003**	**<.001**
LED			1	.340
VMS				1

a) Pedestrian Absent PA situation

b) Pedestrian Present PP situation
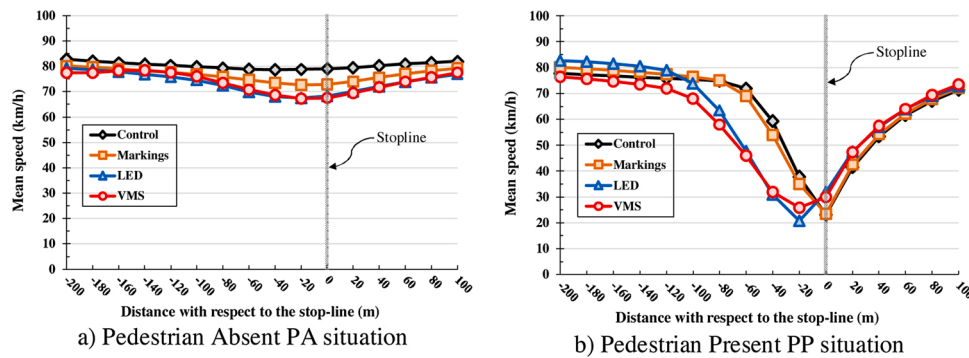
Fig. 8. Mean speed profiles; Condition separated by lines for each situation.

a) Control condition
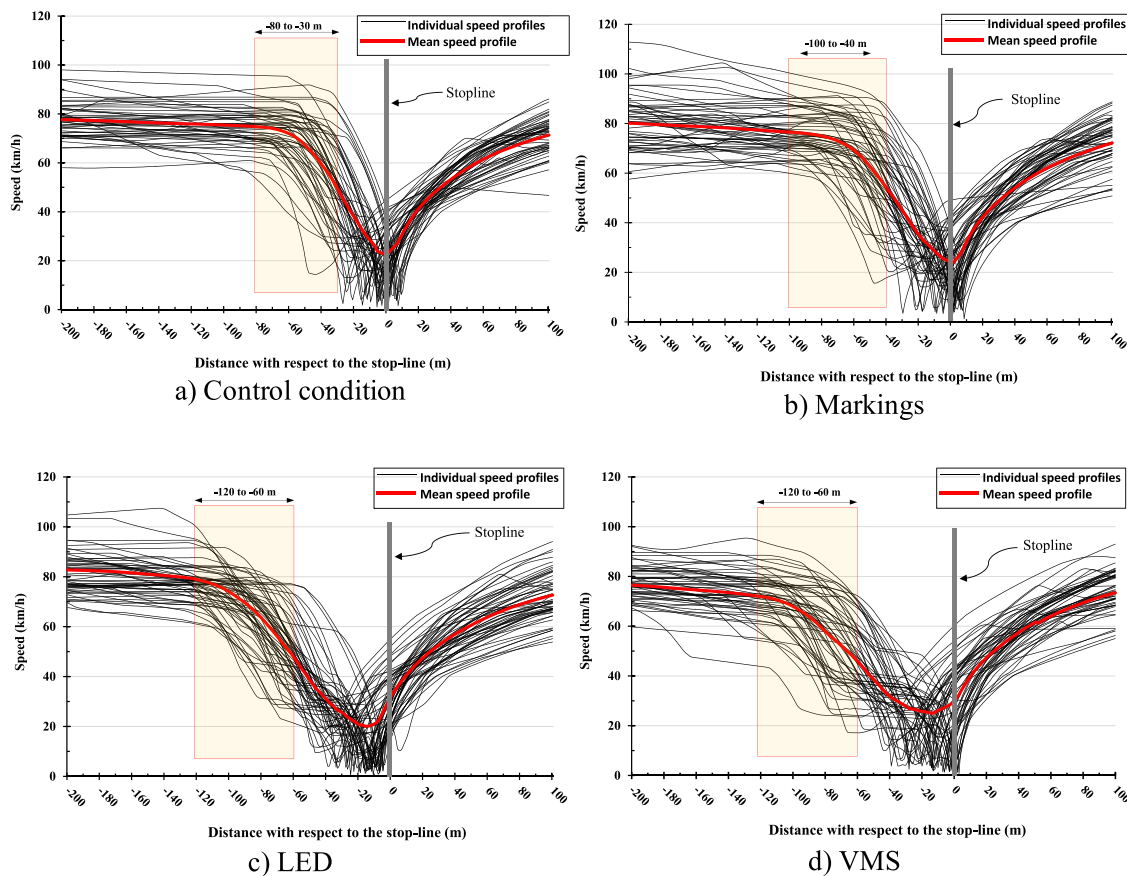
b) Markings

c) LED

d) VMS

Fig. 9. Individual and mean speed profiles for PP situation.

condition with flashing LED light units. In addition, higher proportions of drivers decided to stop after the stop-line in the control and marking conditions.

5.4. Standard deviation of acceleration/deceleration (SDAD)

Table 3 presents the results for the repeated measures ANOVA test conducted to analyze the variations of acceleration/deceleration (acc/dec) between participants. Results showed that the main effect of the factor 'Condition' was not significant ($F_{(3,173)} = 1.3$, p = .287). This means that the overall variations in acc/dec were not significantly different between the tested conditions independent of the other factors, i.e. 'Zone' or 'Situation'. However, the main effects for 'Zone' ($F_{(3,160)} = 319.2$, p < .001) and 'Situation' ($F_{(1,60)} = 659.2$, p < .001) were significant. This reflects that independent of the factor 'Condition',

Table 3

Analysis of SDAD: within-subject ANOVA test (Greenhouse-Geisser). (Bold p-values are significant at 0.05 significance level).

Effect	F	Dfs	p
Condition	1.3	3, 173	.287
Zone	319.2	3, 160	**<.001**
Situation	659.2	1, 60	**<.001**
Condition x Zone	18.7	7, 401	**<.001**
Condition x Situation	11.2	3, 169	**<.001**
Zone x Situation	224.3	3, 168	**<.001**
Condition x Zone x Situation	20.2	6, 375	**<.001**

variations in acc/dec were significantly different along the analysis segment and between both situations. In addition, all interaction effects were significant, of which the three-way interaction effect for 'Condition

x Zone x Situation' ($F_{(6,375)}$ = 20.2, p < .001) is visualized in Fig. 10. This figure shows the mean SDAD profiles for the tested conditions (different colors), for both situations (type of lines) for the total length of the analyzed segments (six zonal intervals on x-axis). The variations in acc/dec were significantly higher in the PP situation where most of the drivers stopped before the crosswalk, as opposed to the PA situation where no one stopped and, therefore, less considerable variations in acc/dec were observed. The highest variations in acc/dec prior to the stop-line [-50 m to 0 m] were observed in the control condition (mean $=3.04$ m/s^2) followed by the marking condition (mean $=2.62$ m/s^2). The results from pairwise comparisons (Bonferroni adjusted) confirmed that, there were significant differences between the control condition and the detection-based conditions at the zone prior to the stop-line [−50 m to 0 m] (Control vs LED: p-value <.001; Control vs VMS: p-value <.001). The differences in SDAD at this location were also significant between the 'Markings' condition and the detection-based strategies (Markings vs LED: p-value = .003; Markings vs VMS: p-value = .020). In addition, there were no significant differences between the control and 'Markings' conditions (p > .999), and between the 'LED' and 'VMS' conditions (p > .999) at this location [−50 m to 0 m].

5.5. Lateral position

In this study, lateral position was measured as the distance from the center of the simulator car to the center of the driving lane. The output from STISIM comprises both negative and positive values for lateral position, representing deviation to either side from the lane central point. These values were converted to absolute values, as the mean lateral position would hide the exact deviation. The ANOVA test revealed that no main or interaction effects were significant at the 5 % significance level which implies there were no significant differences between the tested conditions, between the two situational contexts or between the analysis points. Mean values for lateral position were plotted for each condition along the analysis segment for the PA situation (Fig. 11a) and the PP situation (Fig. 11b). The highest values for lateral position was observed in the marking condition in both situations but at different locations. In this condition, participants deviated from the center of the driving lane by 0.33 m and 0.36 m at 50 m and 100 m after the stop-line, respectively.

5.6. Subjective assessment of the tested conditions

Table 4 presents the results for participants' subjective evaluation. More in detail, the test conditions were first rank ordered (1st ranked is the best) and then evaluated for their effectiveness by means of a 5-point Likert scale (1 = not effective, 5 = highly effective). The data from two participants was missing for the post-test questionnaire and therefore, the ranking and rating were assessed for a sample of 60 participants. The LED condition was ranked first by 68.3 % of the participants followed by the VMS condition (25 %). In a follow-up open-ended question, the

participants were asked to provide a reason(s) for ranking the conditions as 1st. Most of the participants reported that the LED light units are more visible from upstream, in front of the drivers with a clear warning to stop, and also effective in terms of alerting the drivers. Moreover, the LED treatment was rated as the best among the tested conditions with the highest mean rating of 4.58 (SD: 0.6). The traditional crosswalk without any additional treatment was rated lowest with a mean rating of 2.50 (SD: 0.8). Results from the Spearman's correlation showed a significant positive correlation for gender with ratings obtained for the VMS condition ($r_{(58)}$ = .264, p = .042). This means that compared to female participants, male participants reported significantly higher rating for the VMS condition. Regarding ranking of the conditions, the results showed a positive correlation between the LED condition (a dummy variable: "1" if the LED condition was ranked as first and "0" otherwise) and the average distance travelled by the participants per year ($r_{(58)}$ = .277, p = .032). This indicates that as the respondents travelled distance per year increases, LED condition was ranked higher than the other conditions.

6. Discussion

The highest number of drivers not yielding (11.3 %) was observed in the control condition which is in line with a comparable study showing that 9 % of drivers did not yield in a baseline condition (Bella and Silvestri, 2015). As for the context of this study, Qatari drivers tend to yield less and do not give priority to pedestrians as much as what is observed in other studies (Shaaban et al., 2017). Yielding rates improved substantially in the detection-based treatments (i.e. LED and VMS), where only 1.61 % of the participants not stopping. Interestingly, there were six cases where three drivers did not yield neither in the control condition nor in the marking condition. However, the same drivers stopped when the crosswalk was equipped with LED light units. Apparently, flashing LED lights are effective nudges, raising drivers' alertness on approach (Hussain et al., 2020b). This was confirmed by participants' self-reported effectiveness assessments where it came out that LED lights were judged most effective in stimulating drivers to stop before the crosswalk.

Vehicle-pedestrian interactions were further investigated by means of a surrogate safety measure (i.e. PET values). Both the LED and VMS treatments were effective in decreasing the PET values to below the predetermined maximum threshold values for serious and slight conflicts. Furthermore, in both conditions, the mean PET values increased significantly, which indicates the safety increasing potential of these treatments at high speed midblock crosswalks (Almodfer et al., 2016; Archer, 2005; Hydén, 1996). Increasing PET values could be attributed to the presence of an explicit instruction to stop in both the VMS and LED treatments.

LED and VMS treatments significantly reduced drivers' traveling speed in both situations examined. However, mean speeds observed in the PA situation were considerably higher than that observed in the PP situations for all conditions. This could be due to the fact that in situations of perceived high risk (e.g., in case a pedestrian is noticed by the car drivers), drivers tend to choose lower speeds (Starkey and Charlton, 2015). According to Katz et al. (1975), drivers are more inclined to decelerate for a pedestrian than for the mere presence of a marked crosswalk. Even in cases where no pedestrian was present, the VMS and LED lights influenced drivers' traveling speed, lowering it by 11.5 and 10.7 km/h compared to the untreated condition. This further supports the potential of dynamic information displayed on a VMS panel (i.e. Slow Down) or visual nudges in front of the drivers (i.e. flashing yellow LED lights). In the PP situation, the individual speed profiles confirmed that the LED lights encouraged all drivers to yield before the stop-line. This might be because the LED light units were placed on the stop-line and the system was working as a more explicit warning towards drivers. These results are in line with previous studies (e.g. Frederick and Van Houten, 2008; Shurbutt and Van Houten, 2010), showing that
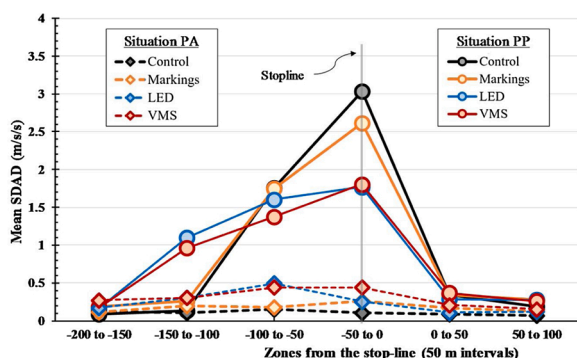

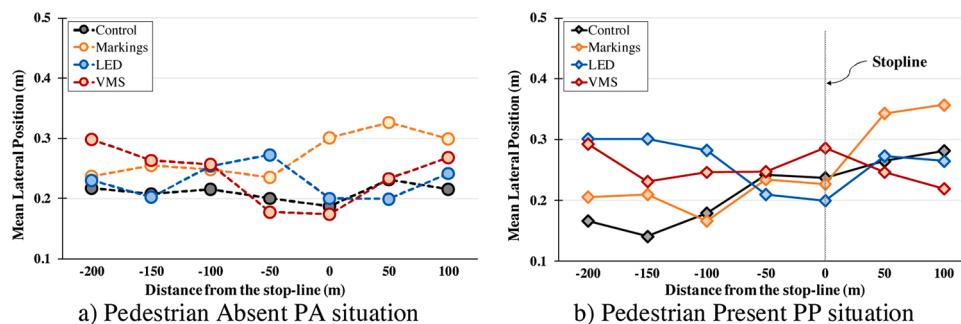**Fig. 10.** Mean SDAD profiles for both situations.

a) Pedestrian Absent PA situation

b) Pedestrian Present PP situation

Fig. 11. Mean lateral position profiles for each condition and both situations.

Table 4
Subjective assessment – Ranking and Rating.

Condition	Sample Size	Ranking	Rating (1 = not effective, 5 = highly effective)						
		Percentage of 1st ranked	Percentage of responses for each level of rating					Mean Ratings	SD Ratings
			1	2	3	4	5		
Control	60	1.7 %	11.7 %	35.0 %	46.6 %	5.0 %	1.7 %	2.50	0.8
Markings	60	5.0 %	5.0 %	18.3 %	30.1 %	38.3 %	8.3 %	3.27	1.0
LED	60	68.3 %	0%	1.7 %	3.3 %	30.0 %	65.0 %	4.58	0.6
VMS	60	25.0 %	3.3 %	3.3 %	18.4 %	41.7 %	33.3 %	3.98	0.9

drivers are inclined to yield sooner when a crosswalk was equipped with rapid flashing beacons. According to Shurbutt and Van Houten (2010), yielding sooner can decrease the probability of a collision. Furthermore, most of the drivers began to decelerate earlier in the treatment conditions (especially in the LED and VMS conditions) as compared to the control condition. The early deceleration in the LED and VMS conditions resulted in safer stopping maneuvers compared to more abrupt deceleration observed in the control condition (Ross et al., 2011).

Participants' stopping behavior was further analyzed, looking deeper into variations in acceleration and deceleration. According to Hussain et al. (2020b), SDAD is a useful parameter to assess the homogeneity of stopping behavior. For instance, higher variations in deceleration among drivers could increase the risk of rear-end collisions with other drivers. Results showed that variations in acceleration/deceleration were higher in the PP situation vs the PA situation. This is because stopping maneuvers were prompted more explicitly in the PP situation. The highest variations in acceleration/deceleration were observed in the control condition, followed by the condition with pavement markings. This indicates more unsafe and inconsistent stopping behavior in these conditions compared to the detection-based treatments. As for lateral position, ANOVA test showed that neither the main nor the interaction effects were significant. This means that the drivers' lateral position was not influenced in any condition. Mean lateral position in this study ranged from 0.14 to 0.36 m, which is comparable to the ranges in lateral position (0.21–0.35 m) found in a naturalistic study (Wang et al., 2014).

The following limitations are to be taken into account. The experiment was conducted on a fixed base medium-fidelity driving simulator. The pedestrian in the simulation scenario was a single person and was programmed to move at a constant speed from right to left, with the pedestrian's behavior not dependent on participants' reactions. Dynamic pedestrian movement in the opposite direction (left to right), or presence of pedestrians in group may result in different driver responses. In addition, the study was designed on a road with a posted speed limit of 80 km/h to replicate existing conditions in the State of Qatar. Testing the same conditions indifferent settings such as residential roads, or school zones may produce different results in terms of how drivers yield and manage speed. Furthermore, future research could also evaluate if drivers approaching marked crosswalks equipped with these measures pay sufficient attention to driving and could investigate the potential impact of distraction on the effectiveness of these measures. Moreover,

future research could focus on assessing performance of the proposed treatments for different external factors, such as, adverse weather conditions and/or nighttime. Finally, the study results are based on immediate and short-term driving behavior. Real-world implementation would reveal if the effects of these tested conditions will endure over time.

7. Conclusion

In this study we investigated the potential of detection-based nudges to improve safety at high-speed uncontrolled crosswalks by increasing drivers' yield rates, reducing vehicle-pedestrian conflicts and stimulating drivers to reduce their travel speed while approaching crosswalks. Two detection-based strategies (i.e. LED and VMS) and a treatment with pavement markings were compared with an untreated control condition (i.e. default condition). The most important findings of the study were that the detection-based strategies improved the vehicle-pedestrian interactions by increasing the yielding rate up to 98.4 % compared to the untreated condition (i.e. 89.7 %). In addition, both LED and VMS treatments excluded serious conflicts (PET $\leq$ 1 s) and reduced the number of slight conflicts (1 s $<$ PET $\leq$ 3 s) significantly. Drivers approaching the crosswalk equipped with LED lights or VMS, reduced vehicle speed well in advance and kept it significantly lower compared to the other two conditions. Furthermore, both the LED and VMS treatments were effective in lowering variations in acceleration/deceleration significantly, which is an indicator of safe stopping behavior.

Based on these results, it can be concluded that safety at midblock crosswalks can be significantly improved by means of detection-based strategies (i.e. LED lights or VMS panel). The treatments could be engineered through detection-based or push-button systems, allowing pedestrians to cross the road safely. Further investigation with different samples or situations such as, different weather conditions, day/night, and/or pedestrian(s) moving with dynamic speed are recommended to further corroborate the findings of this study.

Author statement

Qinaat Hussain: Conceptualization, Software, Writing – original draft, Data curation, Investigation, Methodology, Formal analysis, Writing – review & editing.

Wael Alhajyaseen: Project administration, Supervision, Funding acquisition, Validation, Methodology, Writing – review & editing.

Ali Pirdavani: Investigation, Formal analysis, Writing – review & editing.

Kris Brijs: Methodology, Formal analysis, Writing – review & editing.

Khaled Shaaban: Formal analysis, Writing - review & editing.

Tom Brijs: Methodology, Writing – review & editing.

Declaration of Competing Interest

We have no conflict of interest to declare

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