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Quantitative study of vehicle-pedestrian interactions: Towards pedestrian-adapted lighting communication functions for autonomous vehicles

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Abstract

This paper reports the main conclusions of a fielding observation of vehicle-pedestrian interactions at urban crosswalks, by describing the types, sequences, spatial distributions and probabilities of occurrence of the vehicle and pedestrian behaviors. This study was motivated by the fact that in a near future, with the introduction of autonomous vehicles (AVs), human drivers will become mere passengers, no longer being able to participate into the traffic interactions. With the purpose of recreating the necessary interactions, there is a strong need of new communication abilities for AVs to express their status and intentions, especially to pedestrians who constitute the most vulnerable road users. As pedestrians highly rely on the actual behavioral mechanism to interact with vehicles, it looks preferable to take into account this mechanism in the design of new communication functions. In this study, through more than one hundred of video-recorded vehicle-pedestrian interaction scenes at urban crosswalks, eight scenarios were classified with respect to the different behavioral sequences. Based on the measured position of pedestrians relative to the vehicle at the time of the significant behaviors, quantitative analysis shows that distinct patterns exist for the pedestrian gaze behavior and the vehicle slowing down behavior as a function of Vehicle-to-Pedestrian (V2P) distance and angle.

1. Introduction

Traffic in the road network is a complex activity and relies on sophisticated interactions among road users to reach individual tasks without danger and jam. These interactions are principally under the constraints of traffic laws and regulations. Besides, signaling intentions, negotiating right of way, and even dodging accidents are usually achieved through conventional communications between drivers and pedestrians, such as eye contact, facial expression and hand gestures. The latest technological advancement brings more and more advanced automatic functions into vehicles, which continuously updates vehicles from partial automation to full automation [1]. The deployment of these functions would bring great change to the usage of vehicles and human mobility in the future road system. However, higher level of automation transforms the role of human drivers to mere passengers, who are no longer available to participate into the traffic interactions. Consequently, an interaction break would appear between AVs and pedestrians. It either impairs or cuts off the conventional communications, which could lead to traffic ambiguities and conflicts (see Figure 1).

More than one technical way can be followed to provide AVs the communication abilities, such as radio broadcasting and wireless Internet. Nonetheless, automotive lighting, as an essential part in the vehicle, could be reviewed and regenerated to pro-

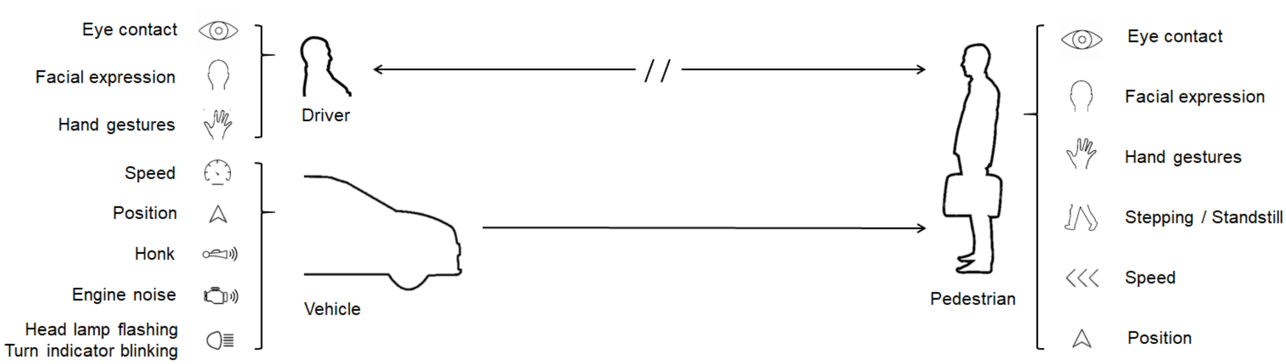
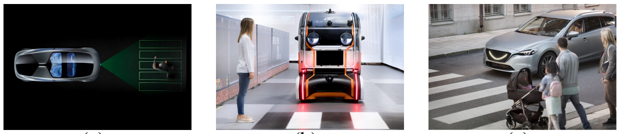


Figure 1. *Due to the absence of human drivers in AVs, conventional communications between the driver and the pedestrian will be impaired or cut off (broken double arrow on the top), the pedestrian can no longer carry out necessary communications with the vehicle (single arrow on the bottom).*



(a) (b) (c)

Figure 2. *Concepts of lighting communication functions: (a) Mercedes-Benz crosswalk projection [6], (b) Jaguar Land Rover eye contact concept [7], (c) Semcon "smiling car" [8].*

vide not only the best illumination, but also the advanced lighting communication functions. Moreover, according to the opinion of pedestrians, it is notable that they are willing to be notified about AV intentions by light signals [2]. The added value of lighting communication functions on achieving a safe and efficient traffic interaction has also been demonstrated in several field experiments [3, 4]. Besides, the Society of Automotive Engineers International has discussed the feasibilities about installing the Autonomous Driving System (ADS) marker lamp(s) and signal lamp(s) to fulfill the need of Autonomous Vehicle-To-Pedestrian (AV2P) communication [5]. Accordingly, why not using the lights?

Several concepts of lighting communication functions have been developed by automotive manufacturers (see Figure 2). However, most of these concepts treat the interaction issues with the pedestrian as dealing with an immovable object in a scripted scenario, rather than a human being who owns variable behaviors. This study raises the question on how lighting communication functions for AVs should adapt to pedestrian behaviors to achieve a suitable and smooth interaction between AVs and pedestrians. Facing the wide variety of traffic situations in the real world, there is a large difference of behaviors in the vehicle-pedestrian interactions. Hence, as a first step towards a comprehensive analysis of vehicle-pedestrian interactions in a wide variety of situations, the goal of this study is to investigate through a field observation the case of urban crosswalks, in terms of the behavioral sequences and the spatial relationship between vehicles and pedestrians. Presuming that at least during the transition period in the near future, pedestrians will interact with AVs as with manually driven vehicles, the complete understanding of the vehicle-pedestrian interaction is helpful to develop the lighting communication functions adequately adapting to pedestrian behaviors.

2. Method

To study how pedestrians interact with vehicles, surveys, interviews, accident reports and simulations by virtual reality are all available methods to investigate road users' experiences and behaviors [2, 9, 10, 11]. Besides, the naturalistic field observation provides a direct way to observe what happens in the real-world vehicle-pedestrian interactions [12]. Using the camera in the observation additionally provides the video recording of the studied scenes, which allows the further revision and analysis of vehicle and pedestrian behaviors. In this study, the video-recorded observation is selected to investigate the vehicle-pedestrian interaction on account of its reviewability.

Observation sites and area

Focusing on the case of vehicle-pedestrian interactions at urban crosswalks, the field observation was carried out on two different sites in Paris Region, which have the same road structure: two-lane bidirectional road, speed limit of 30 km/h, crosswalk marking on the road, and no traffic signal lights. One observation site is located inside a scholar campus, and the other one in the vicinity of a shopping center. The video camera was hidden in the observation site in order to record how pedestrians interact with vehicles without disturbing their natural behaviors. The observation area is composed of two road lanes, a crosswalk, as well as the pavements on both sides of the crosswalk (see Figure 3).

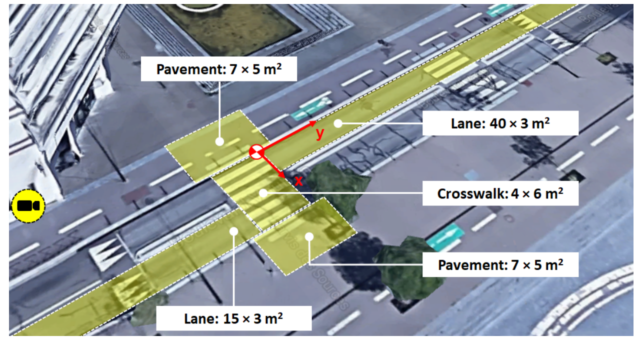


Figure 3. *Overview of one observation site (observation area in transparent yellow, supposed origin in red) and camera setup.*

Vehicle-pedestrian interaction samples

Over a period of two weeks, around twenty-six hours of video footages were collected. The footages were then split into short video clips, in each of which a vehicle-pedestrian interaction scene is involved. As a result, 187 video clips were considered as vehicle-pedestrian interaction samples for the subsequent labelling and extraction processes.

Vehicle and pedestrian behaviors labelling

The labelling process aims to identify and label pedestrian and vehicle behaviors in the vehicle-pedestrian interaction samples. Regarding to pedestrians, this process focused on labelling their attentive and crossing behaviors. Regarding to vehicles, this process focused on labelling their yielding behaviors. Then, the sequences of the labelled vehicle and pedestrian behaviors in their interaction were listed, with the purpose of classifying the different interaction scenarios.

Extraction of vehicle and pedestrian positions

In addition to the behaviors labelling, the vehicle and pedestrian positions in the observation area are of interest in this study. To obtain these data, the extraction process relies on a comparison procedure, whose principle is to compare the vehicle and pedestrian positions to the most adjacent road marking or object of reference in the video frame. As their real-world dimensions and the interval spaces from them to the supposed origin were measured in the observation area (see Figure 3), the vehicle and pedestrian positions in the video frame scale can be converted to those in the real-world scale. Unfortunately, even though the different behaviors can be well observed in the vehicle-pedestrian interaction samples, not all of them are available for the data extraction. For the road lane in the opposite direction to the camera, vehicle behaviors can be identified in the observation area, but there is no achievable road marking to conduct the comparison procedure. Hence, the data extraction was launched for 62 exploitable vehicle-pedestrian interaction samples.

Quantification of the vehicle-pedestrian interaction

It is noticed that a large number of studies have addressed the behavioral, environmental, and social factors that could potentially influence the vehicle-pedestrian interaction [12, 13, 14]. However, specific research to quantify the vehicle-pedestrian interaction is very limited. This study proposes a new perspective that the vehicle-pedestrian interaction can be quantified by considering the position of the pedestrian relative to the vehicle at the time of significant vehicle and pedestrian behaviors, in terms of distance and angle. Thereby, the vehicle-pedestrian interaction can be illustrated and analyzed in a quantitative manner.

The quantification of the vehicle-pedestrian interaction used the results from labelling and extraction processes. At the time of the significant behavior to be studied, the position of the pedestrian relative to the vehicle in terms of distance and angle could be calculated by (see Figure 4):

$$D = \sqrt[2]{(X_v - X_p)^2 + (Y_v - Y_p)^2} \quad (1)$$

$$\alpha = tan^{-1}(\frac{X_v - X_p}{Y_v - Y_p}) \quad (2)$$

where

- D is the position of the pedestrian relative to the vehicle in terms of distance, namely V2P distance,
- α is the position of the pedestrian relative to the vehicle in terms of angle, namely V2P angle,
- X_v, Y_v and X_p, Y_p are the vehicle and pedestrian positions in the observation area.

3. Results and analysis

By reviewing the vehicle-pedestrian interaction samples, six typical behaviors were identified, then labelled as:

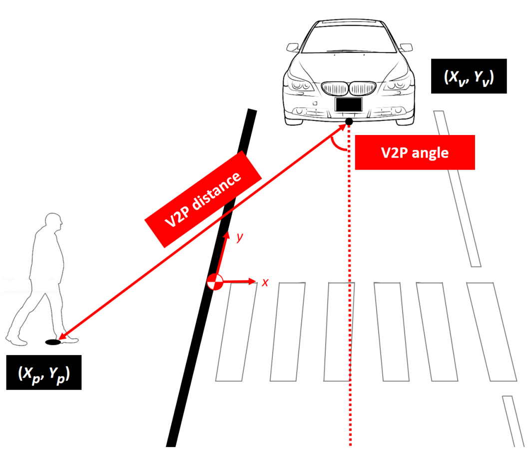


Figure 4. Position of the pedestrian relative to the vehicle in terms of V2P distance and V2P angle.

- gaze, waiting and crossing, for the pedestrian,
- keeping driving, slowing down and stopping, for the vehicle.

With respect to the different sequences composed of these behaviors, eight observed interaction scenarios at urban crosswalks were classified (see Table 1).

Pedestrian gaze

Pedestrian gaze behavior, i.e. the pedestrian looks intently towards the approaching vehicle, was identified in almost all samples (176 among 187 samples). It is additionally observed that the gaze occurred one or two times in the vehicle-pedestrian interaction. In the case of two gazes, the preliminary gaze often took place when the approaching vehicle was far away from the pedestrian, and the secondary gaze happened when the vehicle came closer. This could be explained by the fact that the pedestrian relied on the gaze to estimate the vehicle intention. If the preliminary gaze doesn't provide sufficient information for the pedestrian to understand the vehicle intention, the secondary gaze would occur to confirm it again. In the case of one gaze, it often took place when the distance between the vehicle and the pedestrian was close. It could be considered that the pedestrian used this only one gaze to confirm the vehicle intention. Considering the role of the pedestrian gaze, in this study, the two gazes are considered as the significant behaviors in the vehicle-pedestrian interaction. To distinguish them, the secondary gaze in the case of two gazes was labelled as the confirmative gaze, while the preliminary gaze was labelled as the tentative gaze. In the case of one gaze, the only one gaze was labelled as the confirmative gaze.

Vehicle slowing down

During the field observation, it is observed that depending on the position from which the vehicle started to slow down, the pedestrian might react differently. For instance, when the vehicle slowed down far from the approaching pedestrian, the pedestrian tended to cross directly the road without waiting on the curb and the vehicle slowed down but not until a complete stop (Scenario #1). Otherwise, when the vehicle slowed down relatively close to the pedestrian, the pedestrian rather waited for the vehicle stopping (Scenario #4). This may be linked to the fact that the pedestrian considered the vehicle slowing down as a prominent signal of yielding intention. When this signal is received at a long distance from the vehicle, the pedestrian tends to not interrupt his or her moving action and cross the road without waiting. Conversely, when the vehicle shows too late its yielding intention, the pedestrian would decide to wait on the curb. Considering the effect of the vehicle slowing down, this study considers it as another significant behavior.

Spatial distribution of the significant behaviors

By illustrating the position of pedestrians relative to the vehicle at the time of the significant behaviors, this section analyzes their spatial distributions in terms of V2P distance and angle. Samples corresponding to the scenarios where the vehicle slowed down to yield to the pedestrian are distinguished from those corresponding to the scenarios where the vehicle kept driving without yielding to the pedestrian (see Figures 5 and 6).

For the scenarios (#1 to #4) where the vehicle slowed down (see Figure 5), it can be seen that no tentative gaze and few con-

Table 1. Observed vehicle-pedestrian interaction scenarios.

No.	Behavioral sequence	Meaning
1	P: Gaze → Crossing V: Slowing down	The pedestrian (P) gazed towards the vehicle, then crossed the road. The vehicle (V) slowed down.
2	P: Gaze → Crossing V: Slowing down → Stopping	The pedestrian gazed towards the vehicle, then crossed the road. The vehicle slowed down until a complete stop.
3	P: Gaze → Waiting → Crossing V: Slowing down	The pedestrian gazed towards the vehicle, waited on the curb, then crossed the road. The vehicle slowed down.
4	P: Gaze → Waiting → Crossing V: Slowing down → Stopping	The pedestrian gazed towards the vehicle, waited on the curb, then crossed the road. The vehicle slowed down until a complete stop.
5	P: Gaze → Crossing V: Keeping driving	The pedestrian gazed towards the vehicle, then crossed the road before the vehicle arrived at the crosswalk. The vehicle kept driving.
6	P: Gaze → Crossing V: Keeping driving	The pedestrian gazed towards the vehicle, then crossed the road after the vehicle passed the crosswalk. The vehicle kept driving.
7	P: Gaze → Waiting → Crossing V: Keeping driving	The pedestrian gazed towards the vehicle, waited on the curb, then crossed the road after the vehicle passed the crosswalk. The vehicle kept driving.
8	P: Crossing V: Keeping driving / Slowing down / Stopping	The pedestrian crossed the road without any attention to the vehicle. The vehicle could keep driving, slow down or slow down until a complete stop.

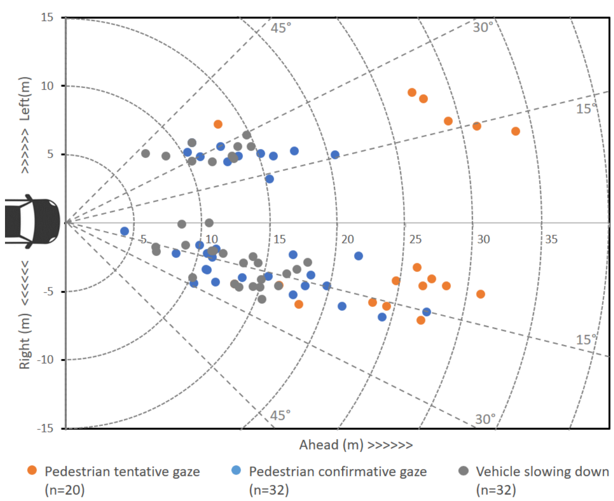


Figure 5. *Position of pedestrians relative to the vehicle at the time of the pedestrian tentative gaze, the pedestrian confirmative gaze, and the vehicle slowing down in the scenarios where the vehicle slowed down.*

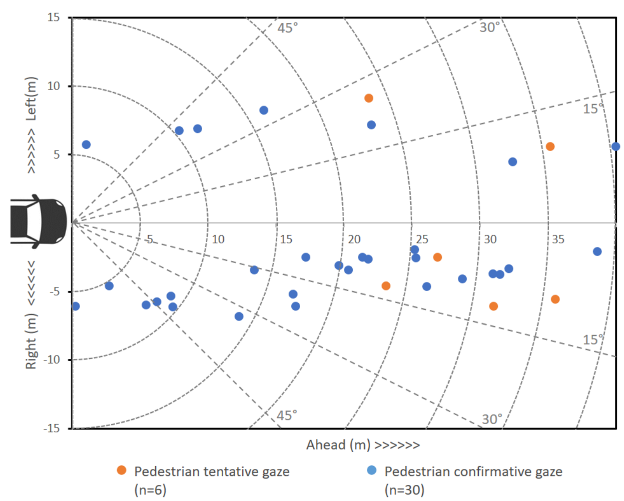


Figure 6. *Position of pedestrians relative to the vehicle at the time of the pedestrian tentative gaze, and the pedestrian confirmative gaze in the scenarios where the vehicle kept driving.*

firmative gazes happened from 0 to 10 m V2P distance. Then, a large number of confirmative gazes were observed from 10 to 20 m. From 20 m, pedestrians rarely had the confirmative gaze, but tentative gazes occurred more frequently. Taking into account the vehicles slowing down, it can be noticed that few vehicles initiated the slowing down from 0 to 10 m and the number was much higher when V2P distance is between 10 to 20 m. Beyond 20 m, no vehicle slowing down has been observed. Notably, the distribution of vehicles slowing down is similar to that of confirmative gazes.

In order to provide a more precise view, Figure 7 shows the empirical probability density of the pedestrian tentative gaze, the pedestrian confirmative gaze and the vehicle slowing down as a function of V2P distance and absolute V2P angle (no distinction is made between whether the pedestrian came from left or right side of the vehicle). It is distinct that there was a higher probability density of the confirmative gaze situated in the zone around 12 m for V2P distance and around 16° for absolute V2P angle. For the tentative gaze, the higher probability density was situated in the zone around 27 m for V2P distance and around 12° for absolute

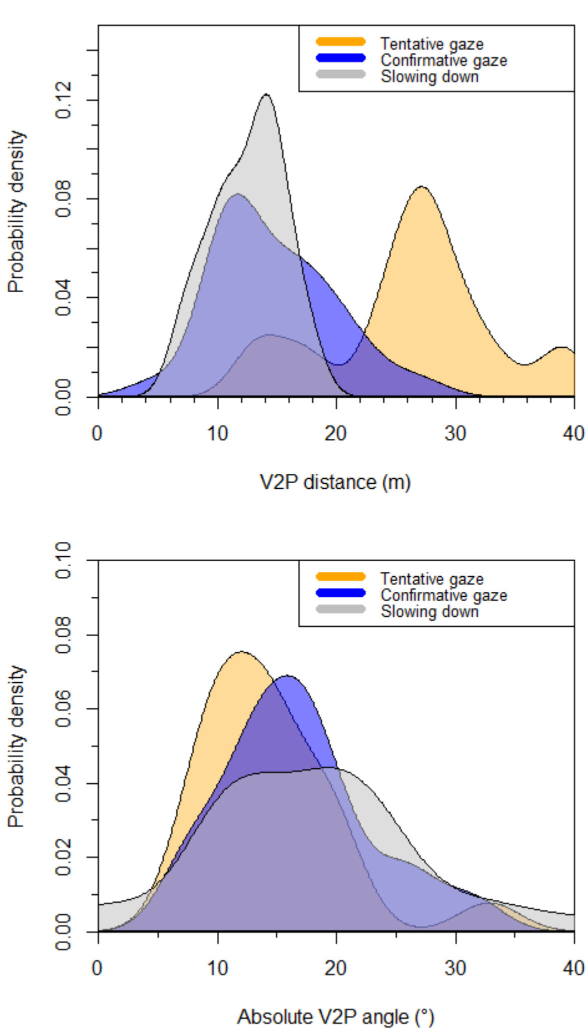


Figure 7. *Probability density of the pedestrian tentative gaze, the pedestrian confirmative gaze, and the vehicle slowing down as a function of V2P distance and absolute V2P angle in the scenarios where the vehicle slowed down.*

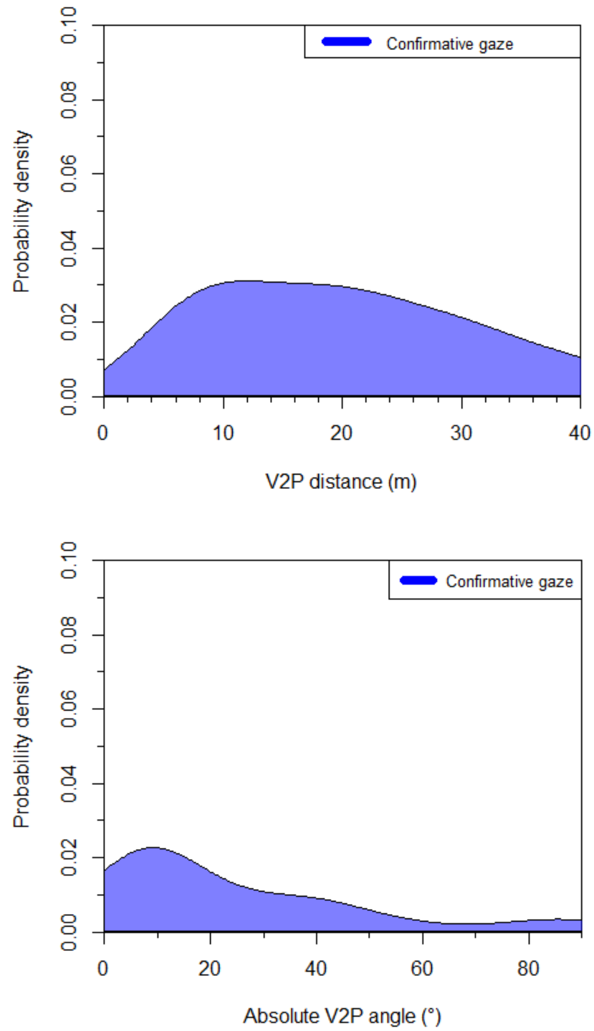


Figure 8. *Probability density of the pedestrian confirmative gaze as a function of V2P distance and absolute V2P angle in the scenarios where the vehicle kept driving.*

V2P angle. For the vehicle slowing down, the higher probability density was situated in the zone around 14 m for V2P distance and around 16° for absolute V2P angle.

For the scenarios (#5 to #7) where the vehicle kept driving (see Figure 6), it can be seen that most of pedestrians performed only one gaze, namely confirmative gaze, in the interaction. Furthermore, it is observed that confirmative gazes occurred almost uniformly from 0 to 40 m.

Regarding to the probability density (see Figure 8), no clear pattern exists for the confirmative gaze as a function of V2P distance and absolute V2P angle (the tentative gaze is not treated here, as it occurred very rarely in this type of scenarios). There was little higher probability density of the confirmative gaze situated in the zone from around 10 to 20 m. For absolute V2P angle, there was nearly no confirmative gaze from around 45° to 90°.

4. Discussion

In the analysis of the three significant behaviors in the scenarios where the vehicle slowed down to yield to the pedestrian, it is notable that in the zone where the pedestrian tentative gaze tended to happen, there was nearly no slowing down performed by the vehicle. Instead, to a certain extent, the zone where the pedestrian confirmative gaze had a higher probability to occur are superposed with the zone where the vehicle slowing down had a higher probability to occur. This observation may be explained by the fact that the vehicle yielding intention shown by the slowing down was successful captured and confirmed by the pedestrian confirmative gaze. As mentioned in the section describing the pedestrian gaze and the vehicle slowing down, pedestrians rely on gazes to look for the vehicle intention and the vehicle slowing down may be a prominent signal to show the yielding intention. When these two behaviors are consistent with each other, the vehicle yielding intention would be understood smoothly by the pedestrian in their interaction.

Regarding to the purpose of this study which is to investigate how lighting communication functions for AVs should adapt to pedestrian behaviors, the solution could be that they communicate the AV intentions by adapting to the behavioral patterns of the pedestrian tentative gaze and the pedestrian confirmative gaze for establishing a smooth AV2P interaction. Based on this assumption, the positions where the lighting communication functions should be activated should be consistent with the zones where the two gazes have high probabilities to take place. As for the AV intentions to be communicated, AV awareness of pedestrians and yielding intention [2, 15] could be necessary for the AV2P interaction. Considering the sequence of the two gazes, the awareness of pedestrians could be communicated by AVs at the relative position where the tentative gaze takes place, and the yielding intention could be communicated at the relative position where the confirmative gaze takes place. To achieve the AV2P communication through appropriate light signals, LEDs based light strip, display and light projection are three possible technological solutions [3, 4, 16]. According to the observed spatial distribution of the two gazes, the usage of display and light projection which are limited in terms of display size and projection distance would probably not be adapted to the tentative gaze occurring far away from the vehicle. On the contrary, the features of LEDs based light strip could reach the requirement of long distance lighting communication. In the condition of close distance lighting communication, the display and light projection could be adapted to the confirmative gaze.

5. Conclusion

This study investigated through a field observation the vehicle-pedestrian interaction at urban crosswalks. By collecting video-recorded vehicle-pedestrian interaction samples, six typical behaviors were identified, and eight interaction scenarios were classified with respect to the different behavioral sequences. It is observed that pedestrians could look for the vehicle intention through two significant gazes towards the approaching vehicle, labelled as tentative gaze and confirmative gaze. The quantitative analysis on the vehicle-pedestrian interaction shows that distinct patterns exist for the tentative and confirmative gazes as a function of V2P distance and angle in the scenarios where the vehicle slowed down to yield to the pedestrian. The two gazes took place with higher probabilities in the specific zones which were specified in terms of V2P distance and angle. A further analysis on the vehicle slowing down behavior shows that a trend of superposition exists between the confirmative gaze and the vehicle slowing down. The insights of these results lead to a discussion on how the lighting communication functions for AVs should adapt to the pedestrian gaze behaviors, in terms of activation positions, messages to be communicated and the possible technological solutions. Overall, the vehicle and pedestrian behaviors as well as their relationship are complex in the vehicle-pedestrian interactions. In this study, the number of analyzed samples is still limited, so that continuous studies with more data are expected to be carried out for further understanding them.

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