



Study, design and realization of an extended automotive signalization

Guoqin Zang

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DOCTORAL THESIS

**Study, Design, and Realization of an
Extended Automotive Signalization**

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Abstract

Autonomous vehicles (AVs) will be integrated into future shared road spaces and bring a huge revolution to the usage of vehicles. Their integration requires not only the robust operation of in-vehicle technical enablers, but also the satisfactory ex-vehicle interactions with other road users. However, AVs are facing interaction problems with other road users which may influence traffic safety and efficiency. Particularly, pedestrians are mostly involved in the interaction problems with AVs, because many practical ways of communication for them, such as eye contact and hand gestures, will be cut off due to the absence of drivers inside AVs. This requires AVs to have new abilities to communicate their status and intentions. For it, automotive signals, as an essential part of a vehicle, shows great potential to be extended for providing visual Autonomous Vehicle-to-Pedestrian (AV2P) communication functions.

Although AV2P communication functions using extended signals have been proven to be beneficial in terms of supporting the recognition of AV intentions and conducting the fast reaction in the interaction, a problematic that they may lose their effectiveness is observed. This can be a consequence of the improper signal design and the unsuitable adaptation to pedestrian communication habits. Therefore, it is necessary to further evaluate extended signals in different forms and closely observe the vehicle-pedestrian interaction with particular attention to the inside communication.

This thesis brings one study on evaluating the understandability of light patterns and pictograms, as two mostly discussed design forms of extended signals. A series of light patterns and pictograms were designed by controlling the content type and the composing elements. Monitor-based online tests were carried out with more than 500 subjects in order to measure how these signal designs are understood. This study demonstrates the different performance of light patterns and pictograms. Also, the effects of their composing elements on promoting or degrading the understandability are revealed. Accordingly, the usage of light patterns and pictograms in AV2P communications and the design guidelines for them are recommended. These contributions are helpful for driving the standardization of the design of appropriate extended signals.

This thesis brings one other study on observing the vehicle-pedestrian interaction around urban crosswalks. With the support of video recording in the places of Paris Region, 187 interaction samples were collected and analyzed with the qualitative and quantitative approaches. This study recognizes the significant vehicle and pedestrian behaviors that act to constitute the communication of information and illustrates their distributions and probability densities in the interaction as a function of distance and angle. Upon these, a pedestrian-adapted employment strategy in terms of when to activate and where to place extended signals are recommended. These contributions are useful for automotive engineers to further define the optical features of extended signals.

This thesis reviews in the end the lighting, display, and projection technologies which are available for implementing extended signals in practice. Also, more interesting application cases of extended signals are suggested for leading the next research in valuable directions.

Résumé

Les véhicules autonomes (VA) vont être bientôt introduits dans les espaces routiers partagés et constitueront une révolution dans l'utilisation des véhicules. Leur introduction nécessite non seulement le fonctionnement robuste des systèmes techniques embarqués, mais aussi des interactions satisfaisantes entre le véhicule et les autres usagers de la route, devant satisfaire des contraintes évidentes de sécurité et d'efficacité du trafic. En particulier, les piétons sont les plus concernés par les problèmes d'interaction avec les VA, car de nombreux moyens de communication pratiques pour eux, comme le contact visuel et les gestes de la main, ne seront plus possibles en raison de l'absence de conducteurs à l'intérieur des VA. Il faudrait donc que les VA disposent de nouvelles fonctions pour communiquer leur statut et leurs intentions. À cet égard, la signalisation automobile, en tant qu'élément essentiel d'un véhicule, présente un grand potentiel d'extension pour fournir des fonctions de communication visuelle de VA avec piétons (VA2P).

Bien que les avantages des fonctions de communication VA2P utilisant des signaux étendus aient été prouvés en termes d'aide à la reconnaissance des intentions du VA et de réaction rapide dans l'interaction, on observe cependant un problème de perte d'efficacité, à cause notamment du design des signaux non conformes et de la mauvaise adaptation aux habitudes de communication des piétons. Il est donc nécessaire d'évaluer davantage les signaux étendus sous différentes formes et d'observer de près l'interaction véhicule-piéton avec une attention particulière à la communication interne.

Cette thèse expose une étude sur l'évaluation de la compréhensibilité de signaux étendus mis sous la forme de motifs lumineux et de pictogrammes. Une série de motifs lumineux et de pictogrammes a été proposée en contrôlant le type de contenu et les éléments constitutifs. La manière dont ces signaux peuvent être compris a été mesurée grâce à des tests en ligne sur écran incluant plus de 500 participants. Cette étude identifie le niveau de compréhensibilité de chaque forme de signal et révèle les effets de leurs éléments constitutifs sur la compréhension. Selon ces données, des recommandations concernant le design de motifs lumineux et de pictogrammes sont conduites, qui pourront être utiles dans les futures étapes de normalisation de signaux étendus pour les VA.

Une autre étude a porté sur l'observation de l'interaction véhicule-piéton autour des passages piétons urbains. Grâce à l'enregistrement vidéo réalisé en milieu urbain dans la région de Paris, 187 échantillons d'interaction ont été collectés et analysés avec les approches qualitatives et quantitatives. Cette étude permet d'identifier les comportements significatifs des véhicules et des piétons et de les quantifier sous forme de distributions spatiales et densités de probabilités. Des recommandations quant au moment d'activation et l'emplacement des signaux étendus sont conduites, qui pourront être utiles pour la spécification des caractéristiques optiques des signaux étendus pour les VA.

Cette thèse passe enfin en revue les technologies d'éclairage, d'affichage et de projection disponibles pour la mise en œuvre des signaux étendus dans la pratique. Des cas d'application des signaux étendus sont aussi suggérés pour inspirer de futures recherches sur ce sujet.

Le mémoire est structuré en 5 chapitres :

Le chapitre 1 introduit le contexte de la recherche sur les feux de signalisation automobile, les interactions du trafic et les futures communications de VA. Aussi, la problématique de la recherche est soulignée et nos contributions sont énoncées de manière générale pour donner une vue d'ensemble de cette thèse.

Le chapitre 2 expose l'état de l'art sur les bases et les nouveautés des feux de signalisation automobile, les exigences des AV en matière de capacités de communication en utilisant signaux étendus, les messages suggérés et les formes de signaux étendus disponibles pour les fonctions de communication VA2P, et les communications dans les interactions véhicule-piéton. Dans chaque section et sous-section, un résumé a été fait pour mettre en évidence les résultats essentiels des travaux de recherche existants.

Le chapitre 3 présente l'une des deux études que nous avons proposées pour répondre à la question du design des signaux étendus. Elle présente précisément nos propositions de signaux, les tests en ligne réalisés, l'analyse sur la compréhension de chaque forme de signal, ainsi que des recommandations d'utilisation et de design des signaux étendus.

Le chapitre 4 présente une autre étude que nous avons proposée pour répondre à la question du moment d'activation et d'emplacement des signaux étendus. Les détails de notre observation, la méthode de quantification des interactions véhicule-piéton, les comportements significatifs des véhicules et des piétons, ainsi que la discussion du moyen de communication sont démontrés.

Le chapitre 5 résume d'abord la trajectoire et la réalisation de cette thèse, puis fournit une perspective vers les recherches futures, incluant les technologies disponibles pour la mise en œuvre des signaux étendus dans la pratique et les autres cas d'application des signaux étendus. Nous suggérons quelques points de recherche intéressants et espérons qu'ils pourront être utiles pour guider les travaux de recherches futures.

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Chapter 1. Introduction

1.1 Research Background

Traffic is a complex process and relies on sophisticated interactions among drivers, vehicles, two wheels, pedestrians, infrastructures, as well as environmental objects. From the perspective of an individual human entity, there are two extremely crucial things that have to be realized while participating in traffic for reaching his or her destination: “seeing” and “being seen”. These two elements allow the extraction and exchange of necessary traffic information. Still, under the adverse environmental conditions and complex traffic situations, the task of “seeing” and “being seen” needs to be supported for ensuring visibility. This is why lights are indispensable for traffic. The automotive forward light, as an essential part of vehicles, produces illumination for drivers that allows them to see the road and the area beside the road in the dark conditions. The automotive signal light, mounted on the conspicuous and visible location of a vehicle, indicates the vehicle’s presence and communicates what the vehicle intends to do to its surroundings. The road light is a raised light source on the edge of a road that give a supplementary illustration for public visibility in dark conditions.

Indeed, automotive signal lights are vital for the traffic. If you do not believe it and are foolish to try to drive without signal lights, you can demount all signal lamps from your vehicle and see how other road users on the same road with you will react to your vehicle. They will be mad with you by honking and pointing because they have no idea when you are braking or turning. This would be a danger to public traffic. In fact, automotive signal lights devote themselves to inform road users of the presence of the vehicle or moving intentions. The task of signal lights consists of sharing this information with other road users on the same road, so as to guarantee road safety and traffic flow. In detail, the functions of automotive signal light are realized through different vehicle signal lamps. For respecting the established standards, car manufacturers and original equipment manufacturers focus on the development of light source, optical control, and lamp structure to bring brilliant solutions for vehicle signal lamps. In the last ten years, the prevalence of efficient and small-volume LED revolutionized hugely the system development of signal lamps and bring great liberty to the design of signal styles. Besides, about the evolution in the aspect of functionality, many suggestions of signal lights that are applied to present new information to road users were proposed. Lately, day running lights have been widely adopted on vehicles for conspicuously indicating the presence of a vehicle during the daytime. This new member of signal lights is expected to improve the safety of road users. There were also many other suggestions for improving signal lights, such as creating more colors to differentiate signal lights or using new light patterns to communicate different types of braking. However, nearly all of them were rejected, because of limited evidences on proving their benefits in the present road system. These valuable experiences enlighten us: with the purpose of extending automotive signal lights, what should be initially done is finding the true need for signal lights, instead of the wishful thinking.

Interactions can be interpreted as smooth and subtle cooperation among all road users sharing the same road space, which have the underlying objective of avoiding accidents and ensuring traffic flow. For the interactions between vehicles and other road users, automotive signal lights

serve as an important information source about the vehicle presence and intentions. In the traffic, road users need to search for information from the environments, including automotive signal lights, rooted traffic lights, dynamics of other road users, and road structures. According to the interpretation of available information, road users decide and carry out the optimal behaviors to cooperate with the others. Taking a simple example of interaction, you can recall your most likely reactions when driving behind a vehicle with the onset of stop lamps. After knowing the vehicle decelerating status through the onset of stop lamps, your next driving decision will depend on the estimated distance to the vehicle ahead. If you are close behind, you must brake immediately for avoiding the collision. If you are far away behind, no urgent reaction needs to be done in time, but you may need to continuously watch out for whether the signal lamps are onset and the gap between the two vehicles.

However, the interaction seems to be a challenge with regard to *autonomous vehicles (AVs)*. With the fast technological progress in terms of detection and automation, vehicles are being equipped with more and more advanced automatic functions, which stands for that the era of AVs is no longer an assumption. For AVs, the driving mission occupied by human drivers is replaced by *autonomous driving systems (ADSs)*. This will bring a huge change to the usage of vehicles and the human mobility. According to forecasting agencies, benefits of AVs involving safety, efficiency, comfort, as well as accessibility, can be expected. Nonetheless, as a totally new road user, it looks like they are still not ready for being integrated into the current road network. Despite that the highly precise sensors and intelligent algorithms allow AVs to drive independently in complex use cases, AVs and their surrounding road users often interact awkwardly and are stuck in ambiguous traffic situations. It is observed that pedestrians hesitated to pass in front of an AV, as they are not sure whether the AV detects and yields to them. Deadlock arose in this situation when both the AV and the pedestrians wait for each other and no one moves ahead. Also, a phenomenon of double standstill is noticed when road users blocked the planned path of an AV. Unlike human drivers who can negotiate passage priority with road users through some practical ways, an AV without any ability of communicating their intentions could only be at a standstill, unless one side turned back or the human supervisor intervened. Notably, pedestrians were mostly involved in the interaction problems with AVs. This is because many conventional communications including eye contact, hand gesture, and fiscal expression between drivers and pedestrians will be cut off when drivers are no longer available in AVs. For AVs, the interaction problems with other road users were still waiting for resolutions in their development, and remain a challenge for their integration into the road network.

For the above interaction problems, the reason can be interpreted as the lack of communication between AVs and other road users, especially pedestrians. With the purpose of having safe and efficient interactions in the future road space shared with AVs, it can be argued that, as regards AVs, there is a strong requirement for the communication abilities to express AV status and intentions. Here, automotive signal lights show great potential to be regenerated by extending their functions for providing communication abilities. For decades, signal lights have been used in traffic as an important communication modality to express messages. It is also reported that road users prefer to be notified about the AV intentions by the light signals. Furthermore, academics and industries have developed *Autonomous Vehicle-to-Pedestrian (AV2P)* light communication functions in their AV prototypes, in which new possibilities of technologies and extended signals to convey messages were demonstrated. For instance, light patterns, differing in motion and color, are one possible signal form based on LED arrays. Pictograms,

composed of figures, and symbols, are also suggested to express the AV intentions by the display or the road projection. Texts in English or other languages are another possible signal form shown on AVs. In fact, their added values have been revealed in many research works, involving promoting the safe behaviors, contributing to the fast reaction, as well as leading to the comfortable experience. Moreover, transportation authorities have claimed several times the necessity of signaling the AV status and intentions. All this evidence can support that automotive signal lights could be extended for realizing not only the basic signalizations but also the advanced light communication functions.

1.2 Problematic

AV2P light communication functions which express the AV status and intentions to pedestrians through extended signals have become a hot research point in the field of AVs. However, finding the new role of automotive signal lights in need is merely the beginning. In the early research works, a considerable problematic that the AV2P light communication functions may lose their effectiveness was observed. Some communication functions which apply extended signals did not achieve their promise of facilitating the interactions as they were regarded to be partially trustworthy and unreliable. Few pedestrians reported that they were actually not influenced by the demonstrated extended signals. According to our analysis, such unexpected performance was likely due to the improper signal design and the unsuitable adaptation to pedestrians' communication habits. In the initial stage of developing light communication functions, big liberty is open for the design of extended signals. Without the standards, academics and industries made their signal designs in all directions. Consequently, some improper signal designs might perform ineffectively as they are meaningless. Besides, pedestrians used to rely on some communication habits in today's interactions with vehicles, such as looking for the vehicle speed variation in time or gazing at the face of a human driver. A retard or a wrong place to show extended signals which does not adapt to pedestrians' communication habits might be disturbing. Correspondingly, we considered that the problematic related to the potential ineffectiveness of light communication functions can be further refined as two questions: *what are the appropriate signal designs for expressing AV information and how the extended signal should be activated and placed?* For getting the effective light communication functions, it would be essential to systematically evaluate the performance of extended signals in different forms and closely observe the vehicle-pedestrian interactions with particular attention to their communication mechanism.

1.3 Contribution

In this thesis, we made firstly a quick review of the basic knowledge of automotive signal lights in the state-of-the-art study. Our assessment of the development directions of signal lights drove us to search a true need for extended signals in the AV interactions. By investigating the AV interaction problems, we listed and regrouped the evidence that supports the AV requirement for communication abilities. Notably, it is found that pedestrians are most involved in the interaction and communication problems with AVs. By choosing the AV2P communication as

the research direction, we gathered and analyzed the existing research works which attempt to use new extended signals to provide AV2P communication functions. In them, the problematic that the AV2P light communication functions may lose their effectiveness was observed. We supposed that this problematic is due to the issues of signal designs and adaptation to pedestrians' communication habits. Hence, it would be necessary to deeply study these two issues. In our further state-of-the-art study, we reviewed the research works that evaluate the signal designs extended in different forms including light patterns, pictograms, and texts. It is noticed that, as an essential factor, the understandability of extended signals has been much less studied. We also reviewed the research works that investigate how the pedestrian communicates with the vehicle in their interactions. It is found that pedestrians highly relied on the implicit and behavioral communications to interact with vehicles, but they are mostly not taken into account in defining the employment strategy of extended signals. Regarding these missing research points, we intend to realize two independent studies in this thesis, one on evaluating the understandability of extended signals and the other one on observing the vehicle-pedestrian interactions with particular attention to the communication mechanism, in order to bring our recommendations on extended signals used for AV2P communications. As regards the above state-of-the-art study, it contributes to being a map which systematically summarizes and links the basics of automotive signal lights, the AV interaction problems, and the AV requirement for communications. It is helpful for quickly integrating into the research of extended signals for AV communications and tracing back to its reason. More importantly, our analysis on the existing research works on AV2P light communication functions, evaluation of extended signals designs, and communication mechanisms in the present vehicle-pedestrian interactions pointed out the problematic and the missing research points which we can particularly study for contributing to the effective AV2P light communications.

For AV2P light communication functions, the demonstrated extended signals must be understandable. In this thesis, we conducted a controlled study by launching a series of tests in an online interface to evaluate the understandability of the extended signals. In this study, we focused on the light patterns and the pictograms which communicate the vehicle yielding intention in a vehicle-pedestrian encounter scenario around the crosswalk, as it is a typical interaction case involving AVs in the future and the clarity of right of way is important for traffic safety and efficiency. The texts, as another possible extended signal form, were not evaluated, because they will be restricted due to the requirement of standardization facing thousands of languages used worldwide. As a result, it is found that the inherent understandability of light patterns was bad in terms of correctly expressing the yielding intention. In addition, none of the different motions and colors for light patterns enabled promoting the interpretation correctness. Such performance of the light patterns suggests that they may not be a suitable signal form to convey complex messages for AV2P light communication functions. One main barrier of using them lies in how to make pedestrians understand their given meaning, rather than proposing more new designs. For this, a learning phase would be highly required with the help of traffic administration. As regards the pictograms, they performed relatively well for expressing the yielding intention. This suggests that it would be better to rely on them to convey complex messages in AV2P communications. However, the diverse types of confusion were observed for the pictograms, which reflects one potential risk of using pictograms. Such confusion needs to be overcome during the design process. Moreover, it is identified that the existence of actor figure and field figure can ease the understanding of the pictograms. As regards this study, its main contribution is providing the

useful evidence for selecting the appropriate signal designs from the perspective of understandability. Also, in this early stage of developing AV2P communication function where no standards exist, it yields the practical guidelines for designing the understandable signals, especially those in the aspects of composing elements and confusion. This study was accepted and published in the journal of IEEE Transactions of Intelligent Transportation Systems in 2022.

Since pedestrians highly rely on the implicit and behavioral communications in their interactions with vehicles, it would be preferable to take account of them in defining the employment strategy of extended signals for AV2P communications functions. In this thesis, we carried out a naturalistic observation on vehicle-pedestrian interactions around urban crosswalks. With the help of video recording, the interaction samples were collected for analyzing vehicle and pedestrian behaviors. We proposed a new perspective, that the vehicle-pedestrian interaction can be quantified as the position of the pedestrian relative to the vehicle at the time of vehicle or pedestrian behaviors in terms of the V2P distance and angle, to study the interaction sample with specific data. As a result, it is observed that the gaze behavior is indispensable for pedestrians to look for useful information in their interactions with vehicles. The slowing-down behavior for vehicles acts as a prominent signal to demonstrate their yielding intention. The quantification of the vehicle-pedestrian interaction shows a trend of superposition between the zones where the pedestrian late gaze had a higher probability to occur and that of the vehicle slowing-down in terms of V2P distance and angle. This can be interpreted by the fact that the vehicle showing down which demonstrates the yielding intention was caught just in time by the pedestrian late gaze which looks for vehicle information. It can be considered that a smooth communication of vehicle yielding intention was constituted by the alignment between the vehicle slowing-down and the pedestrian gaze. Inspired by these insights, we recommend that the extended signals used to communicate AV intentions should be employed in alignment with the pedestrian gaze for achieving a pedestrian-adapted communication. Specifically, the activating timings of extended signals should be consistent with the zones where the pedestrian gazes have higher probabilities to occur. The placing positions of extended signals should be the vehicle bumper and the windshield based on the fixation pattern of pedestrian gaze. The contribution of this research is bringing a rational interpretation on how the communications were constituted by vehicle and pedestrian behaviors, upon which the recommendations on when and where to employ the extended signals can be drawn logically. Above that, the recommendations with the specific distances, angles, and positions are significant for further defining the optical features of extended signals. This study was accepted and presented at the conference of Electronic Imaging 2021 and SIA VISION 2021.

Overall, alongside the identified problematics, our reviews, reflections, imaginations, observations, experimentations, conclusions, as well as recommendations on the new usage of extended automotive signals for AV2P light communications are the purpose and also what we realized in this thesis.

1.4 Thesis plan

For presenting this thesis, Chapter 2 is the review research that we realized throughout this thesis work. It contains the basics and the novelties of automotive signal lights, AV requirement

for communication abilities through extended signals, suggested messages and available signal forms for AV2P communication functions, and communications in the vehicle-pedestrian interactions. In each section and subsection, a summary was made for highlighting the essential findings from the existing research works. Furthermore, we also gave our own interpretations and honest assessment of these findings.

Chapter 3 consists of one of the two studies that we proposed to respond to the question about the design of extended signals. It presents precisely our signal designs, online tests, results of understandability, as well as usage recommendations for the extended signals. In this study, we received great helps from the junior designers in Strate School of Design, Paris for achieving the task of signal designs and from ELS chair, Palaiseau for realizing the online tests.

Chapter 4 consists of the one other study that we proposed to respond to the question about the activation timing and placing position of extended signals. The details of our observation, the method of quantifying vehicle-pedestrian interactions, the notable vehicle and pedestrian behaviors, as well as the discussion of the communication mechanism are demonstrated. In this study, Cité du Design, Saint-Etienne kindly provided us a training on how to make a research for the new usage of automotive signals.

Chapter 5 sums up the trajectory and the realization of this thesis, then provides an outlook towards the future research on the topic of extended signals for AV2P communications. We suggest some interesting points and hope that they could be helpful for guiding the following research works in valuable directions.

Chapter 2. State-of-the-Art

2.1 Automotive Signal Lights

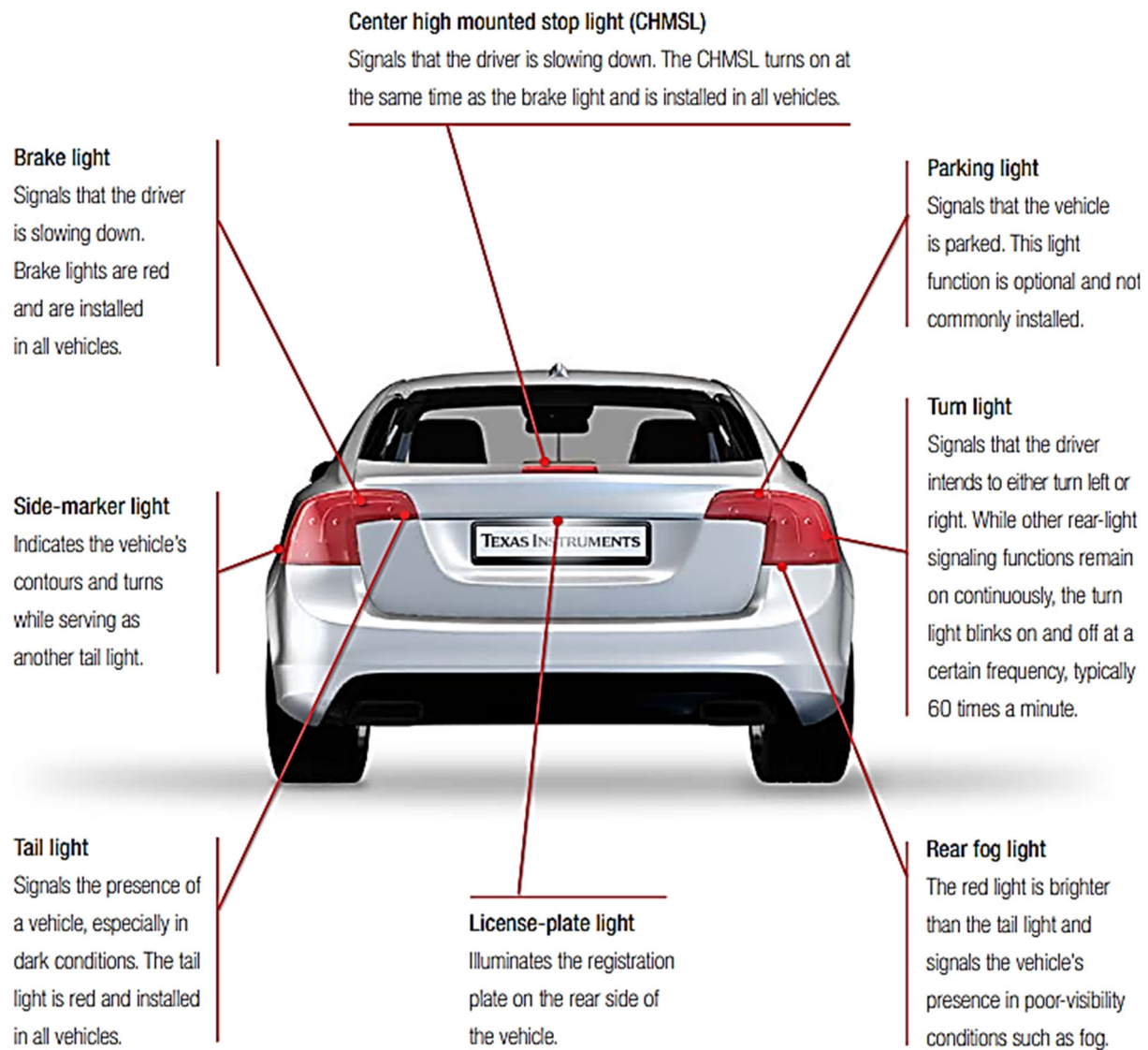
Moving towards the future automotive signal lights, the first step in our research consists of reviewing the existing practices of automotive signals in order to find the possible inspirations and identify the current constraints. Therefore, this section starts with a sum-up of automotive signal lights in terms of history, type, and function. Then, a brief introduction of technological solutions for vehicle signal lamps is given. After that, the main development directions of signal lights are presented, which draws an outlook on how to reasonably bring up suggestions for automotive signal lights.

2.1.1 What are Automotive Signal Lights

Automotive signal lights have an indispensable role in road safety. Being different from automotive forward lights which increase drivers' visibility in the dark conditions, signal lights indicate a vehicle's presence, position, size, moving direction, and intentions regarding braking, turning and lane-changing (see Fig. 2.1a). They play the role of "being seen" by other drivers and road users on the road. To achieve the functions of signal lights, diverse vehicle signal lamps are mounted on the front, rear, sides, and in some cases the top of a vehicle.

Looking back over history, early motor vehicles did not use signal lights. It was until the First World War that tanks started to have a rudiment of signal lights, which consisted of the lamps emitting the red light to the rear and the white light to the side. In the 1930s, the signal lights that indicate the vehicle braking and turning intention appeared. Not being the same as modern automotive signal lights, these old signal lights were normally in red, and sometimes in green or amber. By the 1950s, most vehicles were already equipped with two front position lamps, two rear position lamps, and a license plate lamp. At that time, vehicles in the U.S. also had blinking turn indicators, whereas vehicles in Europe still relied on the trafficator which is a lit amber semaphore swinging out mechanically from the side of a vehicle to indicate the turning intention (see Fig. 2.1c). In the 1960s, the increased density of traffic requires automotive signal lights to be clear and uniform for the road system. Thereby, traffic administrations in different countries and regions established the standards and regulations for signal lights one after another. Since then, the main evolution of automotive signal lights has been the introduction of *center high mounted stop light (CHMSL)*, rear fog light, reversing light, and day running lights (see Fig. 2.1b).

In a wide range, today's automotive signal lights include the front position light, the rear position light, the side marker light, the rear fog light, the reversing light, the day running light, the stop light, the turn light, the hazard light, as well as the license plate light. These lights serve for distinct functions in traffic. They must be visible to road users and their meaning must be clear.



(a)



(b)



(c)

Fig. 2.1 Functions of different automotive signal lights (a), Modern day running light (b), Old trafficator to indicate the vehicle turning intention (c).

2.1.2 Technological Solutions for Vehicle Signal Lamps

For ensuring visibility and clarity, the features of all the automotive signal lights are regulated by standards developing organizations and traffic administrations in detail, involving color, blink frequency, lit size, light distribution, placing location, length, and height [1]-[5]. To meet these regulations, automotive engineers develop vehicle signal lamps with remarkable technological solutions in the aspect of light source and optical control. Besides, considerations in the mechanical, electronic, and environmental aspects need to be taken into account for the lamp structure.

2.1.2.1 Light Source

Two dominant light sources are widely used in current vehicle signal lamps: incandescent lamp and *light-emitted diode (LED)*. So far, the most used light source is the incandescent lamp, on account of being simple and cheap. However, its disadvantage of requiring regular replacement is obvious. Approximately, a standard incandescent lamp has a life of around 750-2500 hours [6]. Comparatively, LEDs have a much higher life span, which can reach as long as 50 000 hours. Another advantage of LEDs is that their luminous efficacy is much greater than that of incandescent lamps. LEDs can reach around 60-131 lumen/watt while creating a light output, as compared to around 10-17 lumen/watt for incandescent lamps. Additionally, LEDs, being small and solid-state components, are more reliable than incandescent lamps against the inevitable vibration during vehicle driving. As a light source, the LED's proprieties of space-saving and robustness give great liberty to the style design of signal lamps. Over years, with the reduction of the cost, LEDs replace quickly incandescent lamps as the first choice of light source for vehicle signal lamps.

2.1.2.2 Optical Control

For being visible, each vehicle signal lamp must attain the specified light distribution by respecting the regulations. This requires that the light source adequately cooperates with the optical control. Generally, there are three main optical control systems for signal lamps, which respectively rely on the reflection, the refraction, and the total internal reflection [8].

For a reflector-based signal lamp (see Fig. 2.2a), it is generally composed of light sources, a parabolic reflector, and an outer lens. The light sources emit their beam toward the parabolic reflector with the defined optical surface. Then, the beam is reflected to the outside through the outer lens. The light distribution is controlled by the position of light sources relative to the reflector, the geometric shape of the reflector, and the optical function of the outer lens.

The refractor optics are frequently applied in turn indicators and rear position lamps. In these signal lamps, the Fresnel lens etched with a series of concentric grooves is the key component for reaching the desired light distribution (see Fig. 2.2b). These concentric grooves acting as individual refracting surfaces are capable of blending the light beams from the light sources.

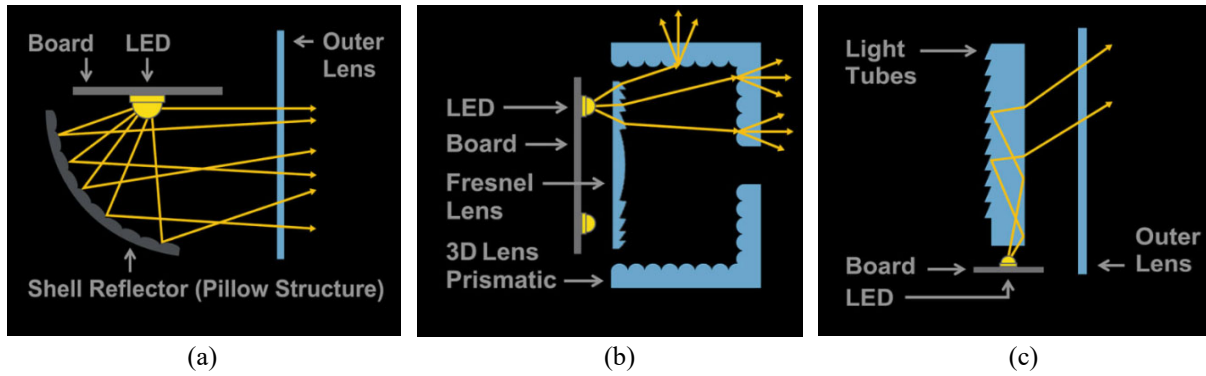


Fig. 2.2 Principles of signal lamps based on the reflection (a), the refraction (b), and the total internal reflection (c) [8].

Compared to the classic optical lens, the Fresnel lens is physically narrower in profile. This allows Fresnel lens-based signal lamps to be thin, lightweight, and do not need reflectors.

Total internal reflection-based signal lamps rely on specific light guides or tubes to constitute the desired light distribution (see Fig. 2.2c). The light guide is a transparent material with a refractive index higher than surrounding environments. This propriety makes light beams emitted into the light guide reflect only between its inner surfaces. Specifically, a number of prismatic elements are built on one side of the light guide. These prisms increase the incident angle of the light beam inside the light guide, which enables light beams to be reflected to the outside.

2.1.2.3 Lamp Structure

Apart from the light source and the optical control, the design of signal lamps needs to take account of the lamp structure, involving mechanical construction, electronic link, and resistance to the environment. The mechanical construction means to make sure that the light sources and the optical control systems are consistently related to each other and the whole is steadily installed on the vehicle. The stable mechanical construction ensures that the desired light distribution will not be affected by vibrations and impacts during driving. The electrical link refers to the connection of light sources to vehicle power supplies and different switches. The resistance to the environment involves the consideration on materials of signal lamps for resisting the extreme heat and cold, as well as the enclosing for reducing the moisture.

2.1.3 Development Directions

Yet, the development of automotive signal lights has never stopped. For the last ten years, one typical evolution of signal lights is the common adoption of day running lights on vehicles. By mounting a pair of static white lights on the front of a vehicle, the role of day running lights consists of improving the conspicuity of vehicles during the daytime. Another noteworthy development happening recently locates in the turn indicators. Sequential turn indicators have finally passed the regulations and been allowed in today's traffic. This new indicator, composed

of a series of light sources, lights up sequentially from inside to the desired turning or lane changing direction. From these two instances, it can be noticed that the present development of automotive signal lights took place in the form of piecemeal addition of signal lights or fine modification of signal patterns. No huge change happened for automotive signal lights. This relatively conservative development mode is to a certain extent the result of strict regulations which reject the unnecessary functions and redundant messages with regard to signal lights. Nevertheless, initiatives and discussions with the purpose of improving automotive signal lights have not been completely hindered by regulations. Numbers of suggestions have been proposed, which can be basically classified into four categories: increasing visibility, providing more information, combining signal lamps with sensors, as well as creating attractive appearances.

2.1.3.1 Increasing Visibility

Concerning the possibility of increasing visibility, a number of suggestions have already been proposed since the period when the regulations for signal lights started to be specified. As early as 1977, R. G. Mortimer [9] suggested that vehicle rear signal lamps should be colored much differently, instead of the present code that rear position lamps and stop lamps are all in red color. His suggestion is to apply the green-blue color for rear position lamps, amber for turn indicators, and red for stop lamps. This is expected to increase the response speed towards each of the rear signal lamps. W. Huhn *et al.* [10] suggested that the light pattern of hazard lamps should be different from that of turn indicators by diverging their blink frequencies. This point of view is based on the consideration that the same blink frequency may easily lead to confusion. Apart from reformulating the colors and light patterns, other suggestions for increasing visibility is to increase the number of signal lamps or optimize their location for different types of vehicles. On heavy trucks, supplementary higher level rear position lamps, stop lamps, as well as marker lamps are broadly applied in order to prevent them from being hidden by surrounding vehicles. On passenger cars, it is the CHMSL that was implemented for increasing visibility. On the one hand, the CHMSL aims at making the signal light which means that the vehicle ahead is braking be more conspicuous for the vehicle immediately behind. On the other hand, the CHMSL is applied for having a stop lamp that is visible to the vehicles which are separated from the braking vehicle by one or more vehicles in the middle. Furthermore, Audi demonstrated in its flagship vehicle a new projection function of turn signal [11]. Relying on the most advanced digital micro-mirror devices, a highly controllable and tiny reflection can be achieved for projecting accurate symbols on the road. It is remarkable in this technological solution that the signal lights would be no longer limited on the vehicle body, but can be seen from its near fields (see Fig. 2.3). This suggestion increases visibility and impact range of signal lights, which contributes to safer interactions between vehicles and their surrounding road users.

2.1.3.2 Providing More Information

With the purpose of providing more information, one suggestion that has been already discussed is to provide stop lamps with the ability to indicate different types of braking. At the moment, the vehicle stop lamps only inform the drivers behind that the vehicle ahead is carrying out the braking action, but nothing is clear about the braking strength. As being well-known, the sudden

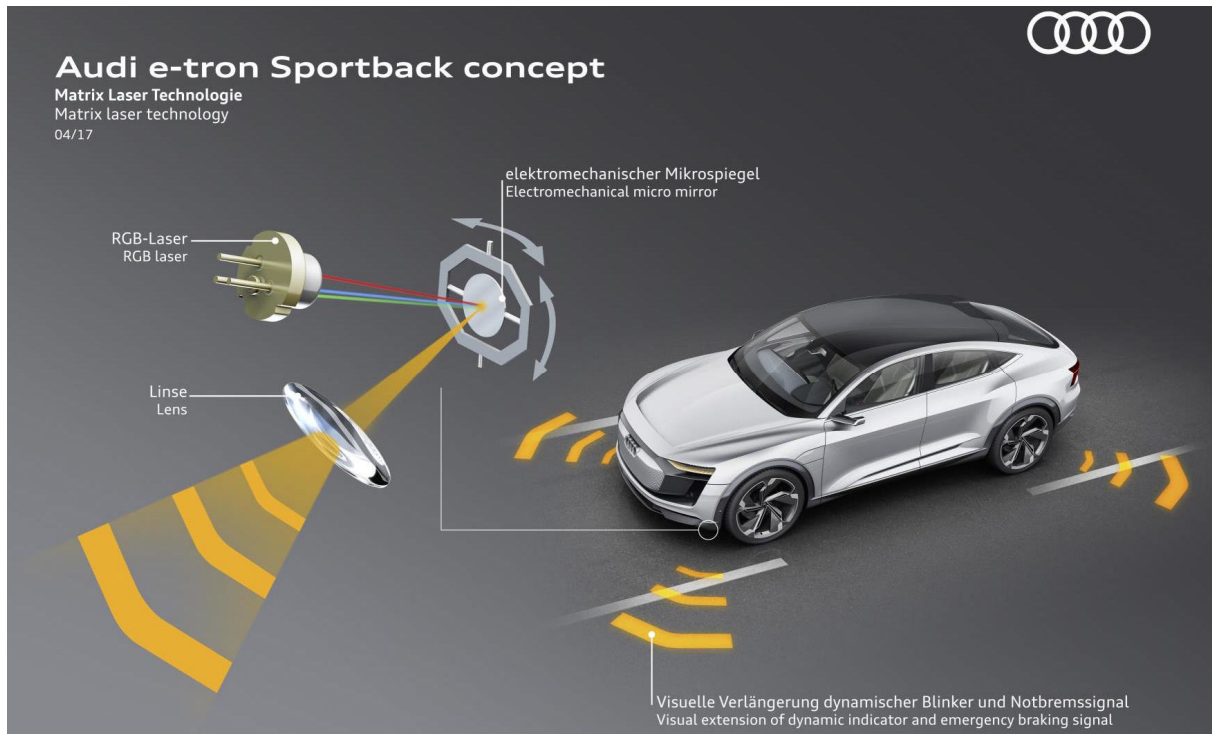


Fig. 2.3 Light projection of turn signals around the vehicle realized by the electromechanical micro-mirrors device [11].

braking is one of the major reasons of end-rear collisions. It seems that wealthy information about the different types of braking is required for road safety. A. D. Horowitz [12] suggested that rear stop lamps can rely on new colors or blink patterns to be updated for indicating the deceleration without braking, the antilock braking, and the braking at low speed. Also, car manufacturers show great interest in implementing multifunctional stop lamps. Their proposals of signaling different types of braking focus on varying the appearance of stop lamps, in terms of brightness or lit area [13]. The stop lamps have a normal appearance when a normal brake happens, but have a different appearance with higher brightness or bigger lit area when there is an emergency braking. Besides, it is noticed on the market that there are sales of scanning-laser rear lamps which can project a stop line behind the vehicle to indicate the safe following distance and a warning sign in foggy conditions. In addition, providing information about which type of the vehicle it is shows its potential value to road safety. Different types of vehicles, such as heavy trucks and passenger cars, own their proper dynamics and behaviors, for example, heavy trucks normally move slowly and have a longer braking distance. Knowing the type of vehicle would be helpful for road users to rightly anticipate vehicle behaviors, which leads to safe reactions [14]. The evidence supporting this suggestion can refer to that the usage of contour lights for distinguishing trucks from other vehicles is beneficial for reducing collisions at night [15].

2.1.3.3 Combining Signal Lamps with Sensors

Another development direction is the combination of signal lamps with sensors. Regarding the adaptive front headlamps which can be automatically switched on and off in accord with sensor

responses about the ambient illuminance, the same strategy is suggested by car manufacturers to be applied to rear position lamps and rear fog lamps. The rear fog lamp is an initial practice for providing drivers with the ability of manually adjusting the rear signal light in adverse conditions. Even so, its conspicuity becomes its glare as the drawback when drivers fail to switch it off in clear conditions. Facing this problem, adaptive rear lamps connected with sensors are expected to intelligently adjust the luminous intensity. Accordingly, they can be maintained at a conspicuous level when the ambient light is high and can be reduced to a sufficient level to avoid the uncomfortable glare when the ambient light is low [16]. Another usage of sensors is to check whether the signal lamps are activated when they are required and whether the signal lamps are deactivated in time after the interrelated maneuvers are completed. This combination of signal lamps with sensors would overcome issues of misdirection, like turning or lane changing without the signal and keeping moving straight ahead with a wrong turn signal [17].

2.1.3.4 Creating Attractive Appearances

The customer requirement for an outstanding and astonishing style is also a key point that drives the development of signal lights. The creative association of light sources with optical control systems provides signal lamps with multiple possibilities in terms of new shapes, homogenous appearance, as well as multiple dimensional effect. As regards light guide-based signal lamps, light guides can be easily shaped to any form which gives car designers lots of freedom to produce unique styles of automotive signal lights. In addition, by determining the geometry and the dispersion of light guides coupled with LED light sources, the homogenous surface light can be obtained for providing comfortable signalization experiences. Apart from this, the *organic light-emitting diode (OLED)* as a new promising light source can realize directly homogeneous surface lights without any reflectors, refractive lenses or light guides. The key propriety that makes OLEDs become the leader in the appearance of signal lights is having a sharp contrast between active regions within a very small interval in one OLED panel [7]. This propriety can result in a number of sharp cut-off and controllable lit segments, which make it possible to develop one OLED model used in different vehicles for providing complex and variable appearances (see Fig. 2.4a). The signal lights with the multiple dimensional effect also

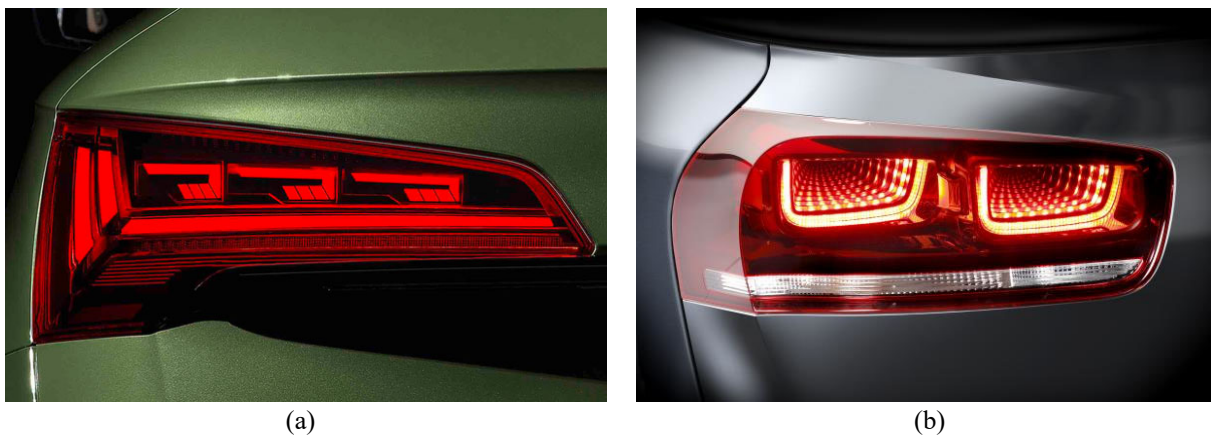


Fig. 2.4 Appearance of a OLED-based tail lamp (a) and a 3D tunnel-effect tail lamp (b).

draw the attention of car markets. One example is the tunnel-effect for rear position lights. To achieve this, the optical control system based on the semi-transparent reflector can be used. The emitted lights are partially reflected by a semi-transparent reflector in a front section. The rest of the lights which pass through the front reflector is reflected again by a non-transparent reflector in a deep section [18]. The light reflects several times between the two reflectors, which creates a 3D tunnel-effect (see Fig. 2.4b).

Despite the logic of all these suggestions and imaginations, it is noticed that a large part of them have been rejected. This can be explained by the fact that the existing traffic interactions do not really need these signal lights or the related studies give limited supports to defend their added values. Automotive signal lights play a significant role in communicating information to road users, but it does not mean to add infinitely the signal lights on a vehicle. The excess of signals will overweigh the communication among road users, which rather complicates the frame of traffic signals. Therefore, it can be argued that what is required to get the suggestions implemented is the evidence that can prove there are truly the needs for signal lights rather than wishful thinking. The extension of automotive signal lights should be effective for road users, so that they can indeed help to optimize traffic interactions when being adopted on a large scale.

2.1.4 Summary: Reasonable Path to Extend Automotive Signal Lights

In this section, we reviewed quickly the basic knowledge of automotive signal lights. They carry out indispensable functions of communicating necessary information about the vehicle, in terms of presence, position, size, moving direction, and intentions. This is essential for ensuring safe and efficient interactions among road users. Under the context of higher traffic density, all vehicle signal lights are required to meet the regulations established by traffic administrations. To fulfill the optical requirements, automotive engineers bring remarkable solutions for signal lamps by developing the technologies of light source, optical control, and lamp structure. Among them, the wide adoption of LEDs replaces incandescent lamps as the major light source and reshapes considerably the optical controls. From reflectors, refractors, and light guides to digital micro-mirror devices, the light distribution is realized more and more precisely. Yet, the development of automotive signal lights has never stopped. A big number of functional and technological solutions were suggested in order to increase visibility, provide more information, adapt to environments with the help of sensors, as well as create astonishing appearances. However, the adoption of these suggestions is hardly accomplished, because the true needs for them cannot be reasonably proven. Automotive signal light plays an important role in the communication through “being seen”, which substantially influences traffic interactions in shared road space. The unproven suggestions for signal lights may conduct unwished consequences in terms of overweighting communication pressure among road users, giving rise to distraction and confusion, or creating uncomfortable light pollution.

Regarding this thesis, *Study, Design, and Realization of An Extended Automotive Signalization*, it is actually a very large and free research topic. To kick off, we support that the reasonable path to extend automotive signals is to orient where is the true need for new signals, specifically for whom. After proving this need, it should be known what design the extended signal should be formed in, when the extended signal should be activated, where the extended signal should be placed, and which technology the extended signal should base on. Alongside these intentions,



Fig. 2.5 Autonomous concept car Smart Vision EQ which communicates its status through an extended textual signal of “On my way”.

we found during our further state-of-the-art study that in the coming era of AVs, new extended signals which express AV status and intentions are needed with the purpose of responding to the requirement for communications between AVs and their surrounding road users (see Fig. 2.5). In the next section, we will introduce step by step AVs, their interaction challenges, and the reflection of extending signals for providing AVs with communication abilities.

2.2 Requirement of Autonomous Vehicles for Communications Abilities through Extended Signals

The latest technological advancement brings more and more advanced automatic functions into vehicles, such as automatic emergency braking, adaptive cruise control, and automatic parking assistance. The deployment of these functions updates continuously vehicles from partial automation to full automation, and replace gradually the role of human drivers. Academies, industries, and markets wait in the hope for the wide adoption of AVs and show great faith in the benefits brought about by mobility automation. Still, in the transition period to AVs, the ADS in the technical aspect needs to be optimized for that these vehicles can completely be competent for driving tasks. Moreover, since the driving, no matter manually or automatically, is anyhow a social activity, the interaction problems with other road users, especially pedestrians need to be considered for constructing intelligent cooperation in future shared road space. In today’s road space, a set of communication cues between drivers and other road users, such as eye contact, hand gesture, and facial expression, are performed for signaling intentions, negotiating right of way, expressing appreciation, and even dodging accidents. However, these communications would be either cut off or impaired once the ADS transforms human drivers to mere passengers who no longer participate in traffic interactions. As these communications

are frequently used in traffic interactions for removing ambiguities and resolving conflicts, their ineffectiveness may lead to interaction problems, such as wrong anticipation on AV behaviors and long hesitation with regard to AVs. These problems may potentially become the obstacles that prevent AVs from being successfully integrated into present traffic and restrict social acceptance of this new road user. For dealing with them, it is needed to reflect the interaction strategies and solutions between AVs and their surrounding road users. In this section, a brief review of the basic knowledge of AVs is given firstly. Then, according to the existing evidence, we highlight the interaction challenges caused by the lack of communications between AVs and other road users. Accordingly, the suggestions of providing AVs with light communication functions through extended signals are presented, along with identified questions about developing AV2P communication functions. The identified questions consist of the guidelines which lead us to carry out further research works.

2.2.1 Coming Era of Autonomous Vehicles

2.2.1.1 Autonomous Vehicle

An AV, also called a self-driving car or a robot car, is one that is capable of performing driving functions by high-precision detection and advanced control systems without any human intervention. The detection systems are usually combined with a variety of sensors, including Radar, Lidar, camera, GPS, as well as inertial measurement units, in order to perceive surrounding environments. By calculating the detected data, the control systems understand the environments and manage the navigation paths. As regards AVs, vehicles become wheels bound with highly intelligent computers and sensors and human drivers are no more needed. Throughout the world, the automation of private vehicles and public transport means a revolutionary change in the usage of vehicles. It is expected to relieve the stress of, assist, and replace human drivers with the support of digital technologies. Excitingly, the widespread adoption and price erosion of advanced driver-assistance systems on vehicles bring us a big step closer to the realization of full AVs. For instance, an automatic parking system can seize through sensors available spots beside the road and automatically steer the vehicle to park there. This frees drivers away from the headache of parking in crowded urban areas. An adaptive cruise control maintains constantly the safe interval between vehicles on the highway, which guarantees driving safety and efficiency in high-speed driving conditions. Furthermore, more complete ADSs are being quickly developed for that vehicles can handle independently complex traffic conditions. The Google car is a representative example of how an AV drives by only using ADSs without any intervention of human drivers. Similar prototypes of AVs have already covered several hundred thousand kilometers on public roads in many countries. This has stimulated the market faith of launching highly automated cars. The future of autonomous driving is so full of promise. It is a future where a number of benefits can be profited thanks to AVs, including better safety, higher efficiency, more comfort, as well as easier accessibility [19]. Besides, the implementation of AVs should be understood as a process taking place in parallel with other important evolutions of road transport: the electrification of the vehicle powertrain which aims at reducing the cost of fuel energy and the shared mobility which opens new business modes. All of these would dramatically redefine the vehicle application, the

human mobility, as well as the relationship between AVs and other road users. In 2050, vehicles should be electrified, automated, and shared [19].

2.2.1.2 Working Principle of the Autonomous Vehicle

The navigation of a vehicle on the road needs to continuously carry out four basic functions: mapping, localization, motion, and interaction [20]. These functions can be translated into four questions: Where am I? Where can I move? How can I move? and How can I interact with others? If an AV would like to navigate as expected, it has to respond correctly to these four questions as well. Based on them, a simplified introduction of the working principle of AVs is produced in the following.

Mapping is literally useful for vehicle navigation, as it provides the necessary information about the world of roads in a visual way. Being the same for AVs, a series of data to represent the world is required for letting them know where they can go. However, a traditional map, e.g. Google maps based on global positioning system (GPS), is not sufficient, because errors in the metric scale are too huge to support the safe autonomous driving. Thus, AVs use a group of advanced sensors, including radio detection and ranging (Radar), light detection and ranging (Lidar), camera, GPS, and inertial measurement unit (IMU) to scan surrounding environments for reconstructing a digital map [21]. This map dedicated to AVs provides and categorizes useful information about the positions and dimensions of road features.

Localization means to know an AV's immediate position on the established map. Through this function, the AV determines its relationship to all surrounding elements, such as distances to vehicles, to lanes, and to intersections. This provides information about what elements are actually around the AV and where they are in the 3D space. In order to precisely realize the localization, tricky data fusion and fault detection algorithms are applied. For the most advanced ADSs, they can localize the AV at the same time as building the digital map, which is called the simultaneous localization and map building [22]. The accurate mapping and localization are the guarantees for the high-speed ADS, which are also the technological prerequisites for the safe motion planning.

Motion, actually motion planning, is a function that defines a series of driving decisions. With respect to the different scale, it can be divided to the global path planning and the local path planning. In the macroscopic scale, the AV decision-making algorithm must select a course from the initial position to the target destination in the road network. This is called the global path planning. In the microscopic scale, the local path planning decides the immediate AV maneuvers in real-time based on dynamics of other road users, road features, and environmental conditions. Thereupon, the decided maneuvers are translated to the paths and the trajectories which are safe for the AV and comfortable for the passenger [23]. The function of motion planning answers to the question: "How can I move" for autonomous driving.

Interaction can be interpreted as smooth and subtle cooperation among all road users sharing the same road space, which has the underlying objective of avoiding accidents and ensuring traffic flow. In the interaction, the mutual understanding of intentions is essential for road users to make decisions. Regarding AVs, the intention estimation algorithms based on the significant behavioral and dynamic cues are designed to predict the intentions of other road users [24][25].

For example, the pedestrian's head orientation is a significant input for AVs to predict the pedestrian crossing intention [26]. Regarding other road users around the AV, it is suggested that novel *Human-Machine Interfaces (HMI)*s and communication functions can be integrated into AVs to show AV intentions by some kinds of signal lights [27][116].

2.2.1.3 Automation Levels and Applications

Despite the great progress in high-accurate sensors and intelligent control systems with regard to AVs, the transition from manually driven vehicles to fully automated vehicles cannot be realized overnight. Generally, it is assumed that vehicles will gradually become more automated. Meanwhile, the role of human drivers will decrease. For systematically assessing and validating AVs during the transition period, a guide that defines the capacities of progressive automation levels would be helpful. Several attempts have been made at defining the automation levels, but it was until the publication of *Society of Automotive Engineers (SAE)* J3016 [29] that a standardized classification of automation levels was widely accepted in the community of AVs. By following the automation levels, the autonomous driving is under the research and development at a rapid pace. Lots of autonomous driving applications have already been placed on the road.

For level 0 [no driving automation or manual control], most vehicles in today's transportation system are at this level. Human drivers must take all the dynamic driving tasks. Merely, there could be some safety systems in place to help drivers. An example is the emergency braking system. As it technically does not "drive" the vehicle, it is not quantified as a function of autonomous driving.

For level 1 [driver assistance], this is the lowest automation level. A vehicle has the driving assistance functions that provide the steering, braking, or acceleration assistance. A driver must stay in charge of vehicle control at all times. The adaptive cruise control is an application of level 1 automation. It helps drivers to automatically remain at a safe distance following the vehicle immediately ahead.

For level 2 [partial driving automation], the advanced ADS integrated into vehicles can take over the steering, braking, and acceleration while driving in specific scenarios. Even though the level 2 automation can handle automatically these basic driving tasks, a driver must remain alert and actively supervise the ADS at all times. The application of level 2 automation can refer to the ENSEMBLE truck platooning [30]. Their trucks can automatically maintain a set with a close distance between each other, among which the truck at the head of the fleet acts as the leader to react to road conditions.

For level 3 [conditional driving automation], the ADS controls the vehicle to drive on its own with respect to the constantly changing environments under limited conditions. It should be highlighted that the transition from level 2 to level 3 is significant for vehicle automation. It is from this level, that the human driver inside the vehicle no longer need to supervise the ADS and the surrounding environments. This means that they can engage in other activities. However, a human driver still has to be present and able to take control of the vehicle at any time if the ADS requests. Provided by Mercedes-Benz, a level 3 autonomous bus, called Future Bus with CityPilot, have made its public journey in Netherlands [31]. It runs on the Europe's longest bus

rapid transit route which links the Amsterdam's Schiphol airport with the town of Haarlem. Although being accompanied with a present driver, this bus is capable of handling by itself the traffic conditions on this route, including many bends, tunnels, and junctions with traffic lights.

For level 4 (high driving automation), its key difference compared to level 3 is that the ADS does not request anymore human intervention in most conditions. Even though there may be system failures, the ADS is programmed to stop safely the vehicle itself. Since human drivers are never needed in level 4 automation, steering wheels and pedals may not be installed in AVs. Ile-de-France Mobilités launched a level 4 Naveya autonomous shuttle in La Défense business district in Paris (see Fig. 2.6). This autonomous shuttle provided the first and last mile transportation for individuals who travail to and from the district on a daily basis [32].

For level 5 (full driving automation), this highest automation means that a vehicle is capable of going everywhere under all conditions automatically. The driving task of the human driver is completely replaced by the ADS. The human inside the vehicle becomes from this level the passenger. Waymo, the world leader in autonomous driving, offered services of level 5 fully automated taxis in the East Valley of Phoenix and Arizona. People who accept to use the service are able to take rides in Waymo's taxis for free and have to offer feedback in exchange [33].

The above presentation with respect to different automation levels present actually a narrow fraction of autonomous driving applications. A large number of prototypes and products of AVs from academies and industries are running day and night in different areas of the world. However, it is notable that that most of these applications are currently employed in limited areas with speed restrictions forced by the legalizations. This isolation with regard to AVs



Fig. 2.6 Ile-de-France Mobilités launched a level 4 Naveya autonomous shuttles in La Défense business district in Paris.

2.2.1.4 Summary: Integration of AVs into the present road network

As regards history, a strong backlash threatened to break vehicles when they were initially introduced to the past society (see Fig. 2.7). The resistance to vehicles took the form of anti-vehicle clubs, which spread up in countries [34]. These groups associated the vehicle with the grim reaper, who drives and takes away lives on roads. The similar story can refer to the invention of unmanned elevators, people still want to take the steers instead of the elevators, because they used to take the elevator with operators and the unmanned elevator is terrifying for them.

[illegible]

28

In any case, AVs will require pedestrians, two wheels, and traditional vehicles to accept sharing future road space with them. If no one accepts AVs, it makes no sense to widely adopt them. Still, the path to AVs is full of uncertainties, and the acceptance on AVs depends on many factors, including not only the performance of in-vehicle technical enablers but also ex-vehicle interactions [19]. So far, a large amount of research works have focused on the performance of Radar, Lidar, AV motion planning algorithm, and AV algorithm for handling sudden situations. These in-vehicle enablers have already allowed initial autonomous driving applications to work without errors and failures. Nonetheless, the suitable interactions between AVs and other road users are unneglectable by considering their role in realizing safe and efficient cooperation on the road. Today, the exploration in the aspect of AV interaction has already been started, but the reasonable interaction strategies between AVs and other road users seem to need further reflection.

2.2.2 Interaction Challenges for Autonomous Vehicles

Traffic circulation is a complicated activity and involves interactions between vehicles and other road users. For example, in the case of pedestrian crossing, the interactions between an approaching vehicle and a pedestrian help them to arrange the safe yielding and crossing behaviors based on cautious awareness and useful communications [35][36]. Regarding AVs in future shared road space, how their interactions with other road users will go on still lack knowledge. New interaction challenges may arise with AVs, which obstructs their integration into the present road system. Notably, an increasing number of research works announced the growing concerns in the aspect of AV interactions. In this section, we will make a review of the AV interaction problems in the scopes of road safety, road users' concerns, as well as road users' behaviors. It is expected that these works could provide helpful cues for the development of AVs by substantially taking account of the interaction conception. The objective of this review is to, based on the matters identified in the interaction with AVs, clarify their essential causes.

2.2.2.1 Unclear Safety Impacts from the Perspective of Other Road Users

Road safety experts emphasize a lot potential safety benefits bring about by AVs, as their ADSs do not make human errors and do not deliberately violate traffic regulations [37][38]. However, such previews are normally made by solely considering the technical aspects on the side of AVs. For the AV-pedestrian interaction in the future, it is at least equally important to look at this matter from the perspective of other road users, involving pedestrians, two wheels, and other vehicles. Especially for pedestrians who are VRUs without any protective "shell", the impact in the cases of collisions or falls with AVs will be fatal. The death of Elaine Herzberg in March 2019 was the first fatal accident related to an AV, in which Herzberg was pushing a bicycle across a four-lane road in Arizona and was struck by an Uber testing AV (see Fig. 2.8). The cause investigation reported that the main reason for this collision lies in the failure of inferring the emergency brake system [39]. The physical braking limitation of the AV does exist [40]. Yet, doubts existed as well from the perspective of the victim. In this fatal interaction, did the victim recognize the oncoming vehicle as an AV and know that it would not yield to her? Did the victim over trusted the autonomous driving abilities that the AV was capable of stopping



Fig. 2.8 The death of Elaine Herzberg in 2019 is the first fatal accident related to an AV.

for her in time? Apart from this accident, risks may appear when pedestrians do not have the right awareness on AVs. The evidence can refer to A. Millard-Ball [41], arguing that the AV-pedestrian interaction is like the game of “crosswalk chicken”. As regards manually driven vehicles, pedestrians generally perceive a large risk, because the social norms allow drivers to not yield to them. As regards AVs, the perceived risk seems to be nonexistent. This is because pedestrians who consistently experienced AVs’ programmed yielding behaviors in their early test stage know that AVs will stop for them. In future traffic where manually driven vehicles and AVs are mixed, such degraded perceived risks could put pedestrians in danger, as they may be insufficiently aware of the fact that the non-automated vehicles do not absolutely stop. So far, the research on the interactions between AVs and other road users is still limited and a lot of questions like the above are unknown [42]. Are other road users able to distinguish the vehicles with respect to the five different automation levels and interact with them accordingly and safely? Are other road users aware of technical limitations of AVs? Will pedestrians accept a smaller gap relative to AVs while crossing before them or a much larger one? Consequently, it is still hard to validate at this moment the safety benefits of AVs in their interactions with other road users.

2.2.2.2 Concerns about Sharing the Road with Autonomous Vehicles

The interaction takes place when road users share the same road space. Road users’ concerns about sharing the road with AVs may initially influence how the interaction goes on. To learn the concerns about AVs, the studies were usually carried out in the form of survey. B. Bazilinsky *et al.* [43] surveyed 8862 respondents from 112 countries to know their attitudes on AVs. It is found that public attitudes appear to be highly split, with a large number of respondents being positive and a large number of respondents being negative. Though not being

proven explicitly in this study, it is possible that early adopters of new technologies belong to the positive group. M. Kyriakidis *et al.* [44] collected the viewpoints of 5,000 respondents on ADSs by the online surveys. There were around 33% of the respondents expressed their enjoyment on autonomous driving. Around 50% of the respondents still insisted that manual driving is the most enjoyable mode. Regarding about what are the concerns for AVs, the respondents mostly indicated safety and hacking issues. Besides, B. Schoettle and M. Sivak [45] conducted surveys to learn people's vision on sharing the road with AVs in the U.S., the U.K., Australia, China, India, and Japan. As a result, around 90% of the respondents concerned about AVs will not drive as well as manually driven vehicles. Their particular concerning problem is that AVs may get confused in unexpected traffic situations. Moreover, around 30-40% of the respondents expressed their great concerns about interactions between VRUs and AVs. Among them, the Chinese people appeared to be the most worried. Another study carried out by J. D. Bullough [46] reports that the risks from AVs to pedestrians are primarily concerned in most of media publications. M. P. Hagenzieker *et al.* [47] assessed whether cyclists' expectation in the interaction with AVs differ from those with manually driven vehicles. By the photo-based simulation, the respondents reported that they did not expect to be better noticed by AVs and they were not more sure that AVs would stop for them as compared to manually driven vehicles. These results imply a conservative and cautious attitude of cyclists in the interaction with AVs. This conservativeness can also be reflected in road users' amplified preference for being separated from AVs. In the online survey study of M. Blau [48] which investigated pedestrians' and cyclists' perception in the road space shared with AVs, the respondents expressed a stronger preference for using separated facilities such as pavements and cycling paths when interacting with AV as compared to manually driven vehicles. Similar findings are observed in the demonstration of CityMobil2 project, which tested a level 4 autonomous shuttle in La Rochelle, Lausanne, as well as Trikala [49]. According to the field interviews, the spectators stated that they felt safer with the shuttle while it was travelling in the designated lanes compared to the shared road space.

2.2.2.3 Awkward Behaviors for Both Autonomous Vehicles and Other Road Users

In the current field tests of AVs, it is often observed that both AVs and their surrounding road users behave awkwardly in their interactions and in many cases being stuck with traffic conflicts. A field study conducted by T. Lagstrom and V. M. Lundgren [27] aims at understanding how pedestrians interact with AVs. In their tests, the features of AVs were pretended by using a



Fig. 2.9 Eye contact, making phone call, and reading a newspaper inside a vehicle from the point of view of pedestrians [27].

right-hand steering to hide the true driver from the view of pedestrians. Then, three typical passenger behaviors inside an AV were performed with regard to pedestrians: making phone call, reading a newspaper, being absent (see Fig. 2.9). By observing the pedestrians' behaviors, it is found that the pedestrians were generally less willing and hesitated to cross the road before the "driverless" vehicle. When the driver was distracted by the phone call, 20% of the pedestrians did not cross before the AV. When the driver was engaged in reading a newspaper or being absent in the vehicle, 60% of the pedestrians did not cross before the AV. Instead, when the eye contact between drivers and pedestrians, set as a baseline behavior in the test, was established with the objective of providing a basic communication clue for pedestrians, all of the pedestrians crossed the road. D. Rothenbücher *et al.* [50] employed a Wizard-of-Oz study to investigate pedestrian behaviors in the interaction with AVs, in which the tests participants encountered a vehicle that appeared to have no driver by wearing a special seat costume. According to the interviews and the videos, it is observed that the pedestrians might have increased uncertainty about the vehicle behaviors. Besides, the conflicting moments might happen in the AV-pedestrian interactions. One typical statement of the pedestrian is that "I waited for a while to see what this AV is going to do, then tried to cross. But then, while I was trying to cross, it intended to start, so I stopped and waited". A similar anecdote was noticed in the blogs which describe the encounter scenario with a Google car [51]. It is mentioned that a phenomenon of double standstill appeared when road users block the unique path of an AV. Unlike human drivers who can negotiate their moving intentions with other road users, an AV without any explicit communications abilities could only be at a standstill, unless one side turned back or the human operator intervened. It can be imagined that deadlock situations may arise where both AV and other road user wait for each other and no one moves ahead. Along with the Digibus project which focused on assessing the performance of AVs in rural areas, K. Rehrl and C. Zankl [52] paid attention to the interaction problems between AVs and other road users. In their field tests, there were some situations where it was not clear what the AV will do next and how the other road users should behave. Sometimes, the other road users were not aware of whether the AV had recognized them as an obstacle and they do not know if they can continue to move or should stop. Sometimes, the other road users abandon their passage priority while interacting with AVs. This leads to the pat-situation where neither the AV nor the other road users move on. Sometimes, the shuttle shows a stop signal via a display on the back windshield. However, it is not clear for the other road users to understand if it is safe to overtake the shuttle or should they also stop behind the shuttle.

2.2.2.4 Summary: Requirement for Communications in the Interaction with Autonomous Vehicles

Theoretically, most automation related accidents are caused by not providing appropriate feedback and not facilitating proper interactions with the human operator [53]. This point was increasingly revealed in the investigations about the safety impacts of AVs from the perspective other road users. The road to autonomous driving would require more than detection of the environment and decision-making algorithms, and presents new requirements by taking account of the interaction conception. The findings of the studies that look directly into the attitudes on sharing the road with AVs shows that not all of the people enjoy this innovation on automation and many of them have their concerns about autonomous driving abilities and performances

[43]-[46]. For these road users expressed concerns, they generally have a conservative and cautious disposition towards AVs in terms of low expectation for AV safe behaviors and high preference for being isolated from AVs [47]-[49]. These findings reflect the fact that road users are not ‘per definition’ confident of the AV driving competence. In the aspect of human factors, this un-confidence may be a barrier which restricts the wide acceptance of AVs. Essentially, autonomous driving abilities are determined by the data collected by sensors and the algorithms treating these data. However, the current AVs own no means to present explicitly how they make the motion decisions depending on the sensor-detected data. This forms an un-transparency between the ADS and the external road users. Such un-transparency may be one of the origins that causes the low confidence on AVs. Accordingly, it seems that some kinds of communications indicating autonomous driving abilities of AVs would be required for enhancing other road users’ confidence on AVs. Aside from the low confidence, it is found that road users may behave awkwardly in their interactions with AVs. The research works focusing on observing pedestrian behaviors report that the pedestrians usually behaved hesitantly before an AV with no driver inside due to the absence of conventional communication cues, including eye contact and gestures [27]. This absence of communication prevents AVs and pedestrians from being aware of each other’s presence and next moving intentions. Moreover, it is observed that the conflicting behaviors may appear for both AVs and pedestrians [50]. On the side of pedestrians, they did not know how they should behave or not behave, as they had no idea of what AVs intended to do in the next [52]. On the other side of AVs, AVs get confused by the pedestrian conflicting behaviors, which make them wait on the road at all times for making sure zero accident. While being stuck with these situations, AVs which are currently not designed with any means to express their intentions, are incapable of arranging the passages [51]. Correspondingly, the above issues arise the requirements for communicating the AV intentions to establish the smooth interactions.

Indeed, the European Road Transportation Advisory Council [19] declared the importance of reflecting the interaction problems as regards AVs and human road users. In their road map for the development of autonomous driving, it was particularly demanded:

“How to understand the interaction between humans and automated vehicles (in-vehicle and outside vehicle) at different levels of automation?”

“How to find design solutions and standards for human factor challenges such as misuse, skill degradation, level of trust and acceptance, motion sickness? How to adapt the vehicle automation to different user needs and group? How to design the safe, intuitive interaction of automated vehicles with other road users?”

“How to derive interaction design concepts for the automated vehicles so that both the human driver and other humans in the surrounding sufficiently understand the capabilities and limitations of the vehicle?”

It can be seen that that the above demands are coherent with the reviewed research works on the AV interaction problems. All of them orient together a requirement for communications between AVs and other road users. This requirement from the perspective of other road users should be involved in the development of AVs and their adoption. Without responding to this requirements, we risk to fail the integration of AVs and has to reject this technology. Presently, the solutions of providing AVs with communication abilities are completely open and the standards for these solutions are missing.

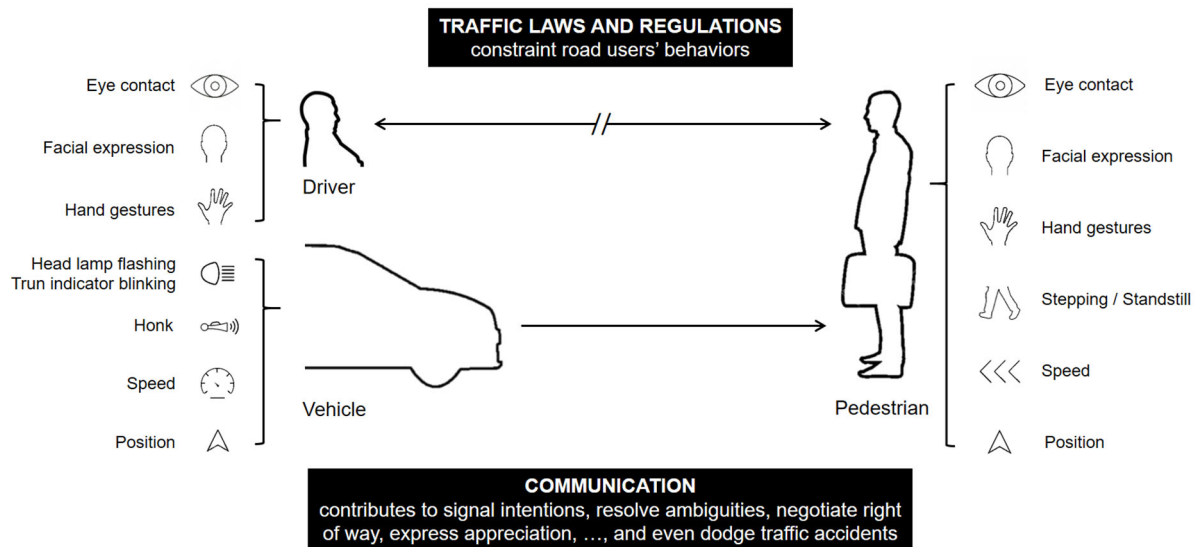


Fig. 2.10 Behavioral communications between the driver and the pedestrian including eye contact, facial expression, and hand gesture, will be cut off or impaired with the introduction of AVs (broken arrow on the top)

Notably, as covered in the reviewed research works with respect to different road users, pedestrians were mostly involved in the interaction problems with AVs no matter they are for safety impacts, concerns, or awkward behaviors [27][46][48]-[50]. This suggests that pedestrians should be considered as the primary group of road users for developing AV communication abilities. In addition, it should be highlighted that the behavioral communications between the driver and the pedestrian will be cut off with the introduction of AVs (see Fig. 2.10). Unlike the traffic situations with only vehicles where their interactions can basically work by respecting the traffic laws and regulations, many behaviors including eye contact, hand gesture, and fiscal expression, exist as the important communication cues for pedestrians to understand vehicle intentions. It has been identified that these behavioral communications work contributively on signaling intentions, negotiating right of way, and even dodging accidents in vehicle-pedestrian interactions [54]-[58]. However, since the ADS transforms human drivers to mere passengers who will not be available in traffic interactions, the behavioral communications can no longer be relied on by pedestrians. This may probably cause the misunderstanding of vehicle intentions. Their ineffectiveness may result in pedestrians' irritation or safety issues with vehicles [54][59]. Therefore, the promise of AVs for being safer and more efficient with regard to pedestrians may be limited. This particularity reveals again that the recreation of communications between AVs and pedestrians should be focused on for facilitating their interactions. Moreover, another reason for highlighting the pedestrians lies in their vulnerability. A higher probability of getting heavily injured or death always exist as regards pedestrians in accidents with motor vehicles, no matter being manually driven or autonomous. The WTO global status report on road safety [60] compiles that pedestrians made up around 23% of all road fatalities worldwide in 2018. As an important group of road users, they were involved in nearly one quarter of all road fatalities. In the European region, the share of pedestrian road fatalities was around 27%, somewhat being higher than the world average level. According to the European Transport Safety Council [61], the majority of pedestrian fatalities in Europe were the result of collisions with motorized vehicles, in particular

passenger cars. Besides, most of the pedestrian fatalities took place on urban roads. In terms of concrete value, 68% of the pedestrian fatalities were caused by impacts with passenger cars and 69% of pedestrian fatalities occurred on urban roads in the period 2011- 2013. Even though AVs will react faster than human drivers, these vehicles might not be able to stop in time because they still have physical braking limitations [40]. AVs could still cause dangers to pedestrians.

2.2.3 Providing Autonomous Vehicles with the Communication Abilities

AVs will be gradually updated from partial automation to full automation, and finally enter the road network. For allowing this, AVs must be technically competent in driving themselves in the complex traffic conditions, and they also have to smartly interact with other road users on shared road space. In the technical aspects, great progress has been made in improving the internal ADS enabler. However, as mentioned in the previous section, the interaction problems remain the bottleneck for the adoption of AVs. With the purpose of facilitating the safe, efficient, and comfortable interactions between AVs and other road users, it can be argued that AVs highly require the communication abilities to express their status and intentions. Indeed, this requirement for communication abilities is especially true for the AV interactions with pedestrians. With regard to this requirement, AV2P light communication functions through extended automotive signals were suggested by academics and industries [62]-[65]. As regards this thesis, this is where the need for new signals is found. However, despite the good willingness, the need for new signals cannot be subjectively supported. It is the collaboration among the reasonable suggestions, the evidence proving their benefits, and the work with official regulations that can make pedestrians grant an approval stamp for these signals used in AV2P communications. If not, they will only stay in the imagination for years to come. Therefore, following the suggestion of AV2P communication functions, this section demonstrates a group of existing research works that evaluate their effects. Then, several practical trials of light communication concepts developed by industries are listed. In the end, we will listen to the authoritative voices on how to achieve AV communications by external HMIs or supplementary automotive signals.

2.2.3.1 Why Not Providing Communication Abilities Through Signal Lights?

There are several technological solutions that can be applied for communicating information among road users. One classical communication solution is using radio broadcasting to construct the invisible *Vehicle-to-Anything (V2X)* connection, including *Vehicle-to-Vehicle (V2V)* and *Vehicle-to-Infrastructure (V2I)* [66]-[68]. This solution basically depends on the wide-range wireless data communication which enables exchanging information about the position and speed of road users. Similarly, wireless Internet technology provides one other solution to realize the connection among road users. Through dedicated software installed both on smartphones carried by pedestrians and on vehicles, their real-time positions can be shared. Based on this information, both vehicles and pedestrians can be aware of each other's position and movement and, thus just in case, receive warning signals about the imminent dangerous situations [69]. Apart from smartphones, another possibility to receive the alarm signals can be

the wearable sensory devices [70]. Although these solutions of the wireless communication technologies are usable for signaling coming dangers, which contribute to preventing accidents from pedestrians, the adoption feasibility seems to be unlikely. These solutions require pedestrians to pay additional expenses for preparing the dedicated devices, which is however not easy to be accepted. Besides, these solutions would raise the privacy issues regarding road users' personal information. Moreover, it is reported that pedestrians do not really prefer the wireless communication technologies, as it seems that they shift the responsibility away from AVs for potential accidents [71]. These constraints prevent the wireless communication technologies from being adopted for providing AVs with communication abilities.

Nonetheless, automotive signal lights, as an essential part of vehicles, can be reviewed and regenerated to provide not only the basic visual signalization, but also the advanced light communication functions. More than 50% of the cortex, the surface of the brain, is devoted to processing visual information [72]. 70% of the human sensory receptors are in the eyes, and 1/10 second is all it takes to understand a visual scene [73]. More importantly, starting in 1868, red and green signal lights have been used to communicate messages for controlling horse carriages, this is even before the invention of automobiles [74]. Human beings are already familiar with signal lights. Furthermore, in the existing research works which tried to identify the new way to communicate AV intentions, road users showed their preference for lights. During the public demonstrations of an autonomous shuttle managed by the European CityMobil2 project [49], the pedestrian spectators claimed that they would like to be notified of the AV awareness and intentions through the light or auditory signals. Besides, in the experimental study conducted by K. Mahadevan *et al.* [75], four communication modalities mounted on the automatic agencies, which are a light signal emitted by LED strips, an auditory signal emitted by a smartphone, an animated face with oscillating eyes, as well as a physical signal presented by a mechanical pointing hand, were compared in terms of their usefulness. It is reported that the light signal was often ranked higher than the other communication modalities. Besides, considering that there are thousands of different languages throughout the world, Ford believes that the signal light would be a suitable modality to establish a universal adoption of AV communications with other road users [76]. Moreover, SAE discussed within their J3134 task force the feasibilities of installing ADS marker lamp(s) and signal lamp(s) to fulfill the requirement for AV2P communications [77]. The ADS marker lamps are dedicated to indicating whether AVs are in autonomous driving mode or manually driving mode. The ADS signal lamps consist of signaling the AV moving intentions. Evidently, automotive signal lights show great potential for providing AVs the communication abilities in a direct and simple manner. So, why not signal lights?

2.2.3.2 AV2P Light Communication Functions and Their Effects

In recent years, the effects of AV2P light communication functions which express AV status and intentions through extended signals have been demonstrated in several research works. *AVs Interaction Principle (AVIP)* is a communication tool created by A. Habibovic *et al.* [62], whose function is to communicate the AV automated mode and the AV intentions with pedestrians. This communication tool consists of a RGB LED array, which can demonstrate several light patterns. In their concept, the message about "I'm in automated mode" is designed as a constant

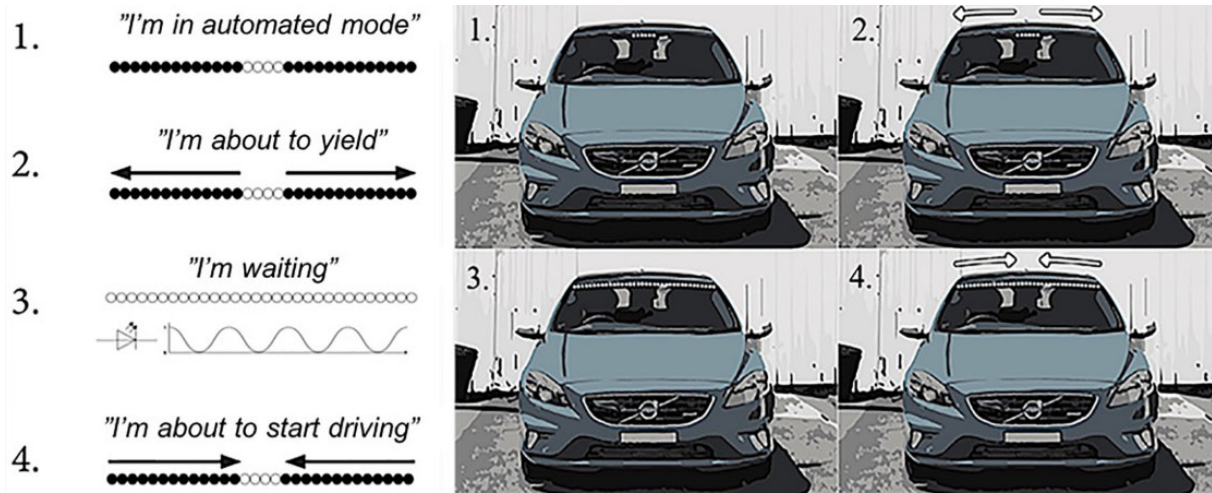


Fig. 2.11 AVIP communication tool (RGB LED array) communicates the AV automated mode and the AV intentions through the light patterns [62].

lit segment in the middle of the LED array. “I’m waiting” is designed as a pulsed lit segment in the middle of the LED array. The intention of “I’m about to yield” is designed as a repeated light expanding from the middle to the two sides of the LED array. “I’m about to start driving”, on the contrary, is designed as a repeated light shrinking from the two sides to the middle of the LED array (see Fig. 2.11). In their field experiments, an AV equipped with and without the AVIP approached to the participants who played the role of the pedestrian. By evaluating the participants’ interaction experience, it is found that their safety feeling was bigger when being with the AVIP-equipped AV than without. Interestingly, the participants stated in the interview that they had the same safety level in the situation of interacting with the AVIP-equipped AV as with the manually driven vehicle.

The communications using the display [75][78] on the vehicle external surface can be another possible solution to help AVs interact with pedestrians. M. Matthews *et al.* [79] tested their *intent communication system (ICS)*, a LED matrix-based display, which is developed to inform pedestrians of whether they should stop before an AV through the text of “Cross now”. By a field experiment and a simulation experiment, the effects of display on the expectation and the trust in the AV were studied within 4 groups divided with respect to whether the AV is equipped with the ICS and whether the pedestrians have prior knowledge of the ICS. It is noticed that the pedestrians reacted more predictably with regard to the AV when its intention was communicated through the ICS. Besides, there is a higher pedestrian trust score for the group with the ICS and the prior knowledge compared to the group without both. Moreover, it is observed that there was 38% of improvement in resolving deadlock situations with the ICS.

In another way, the light projection was suggested to achieve the AV2P communications (see Fig. 2.12). S. Azougui *et al.* [63] investigated the impact of light projection on safety, specifically in a vehicle departing scenario in the underground parking. A light projection system installed at the rear of a vehicle was developed which enables the road projection of an arrow symbol. The arrow symbol represents the vehicle reserving intentions and direction. In their field test in the underground parking, the pedestrians’ and cyclists’ behaviors were video recorded and analyzed in 3 different conditions: no communication between the vehicle and participants, the activation of reserve lamps, and the activation of both reserve lamps and light



Fig. 2.12 Light projection can achieve AV2P communications by projecting signals on the road surface.

projection. It is reported that the visibility of light projection was better than the reverse lamp. Furthermore, after recognizing the projected symbol, the pedestrians' and cyclists' adopted behaviors to avoid potential risk, including stopping, braking, and seeking the vehicle, were observed in the vehicle departing scenario. These behaviors imply that the tested light projection has positive impacts on promoting road users' safe behaviors.

T. Petzoldt *et al.* [80] tested a light communication function proposed to communicate the information about vehicle deceleration on the front of the vehicle. This function is based on a device mounted above the front license plate. It is lit up with a green brake light as soon as the vehicle decelerates (see Fig. 2.13a). The participants viewed the real-world videos of an approaching vehicle equipped with this device and were tasked with detecting the vehicle deceleration. It is concluded that the light communication facilitated the participants' detection of vehicle deceleration, as evidenced by a shorter reaction time compared to the tests without the device. Interestingly, once the participants experienced the usefulness of the frontal brake light and got used to relying on it, the detection of deceleration without its assistance would become slow. Besides, the majority of participants agreed with the potential of the light communication in terms of increasing safety and preventing crashes.

The similar findings were found in a *virtual reality (VR)*-based study conducted by M. P. Böckle *et al.* [81]. They evaluated a light communication function developed to express the AV intentions. Their light communication function employed a speaker and LED arrays positioned on the four corners of a vehicle to convey the messages via sounds and colored light patterns (see Fig. 2.13b). "Not stopping" is signaled by a flashing yellow light, "Stopping" is signaled by a vertically moving blue light, "Waiting" is signaled by a slowly fading blue light, and "Start driving" is signaled by a flashing yellow light with a bell sound. The participants were tasked

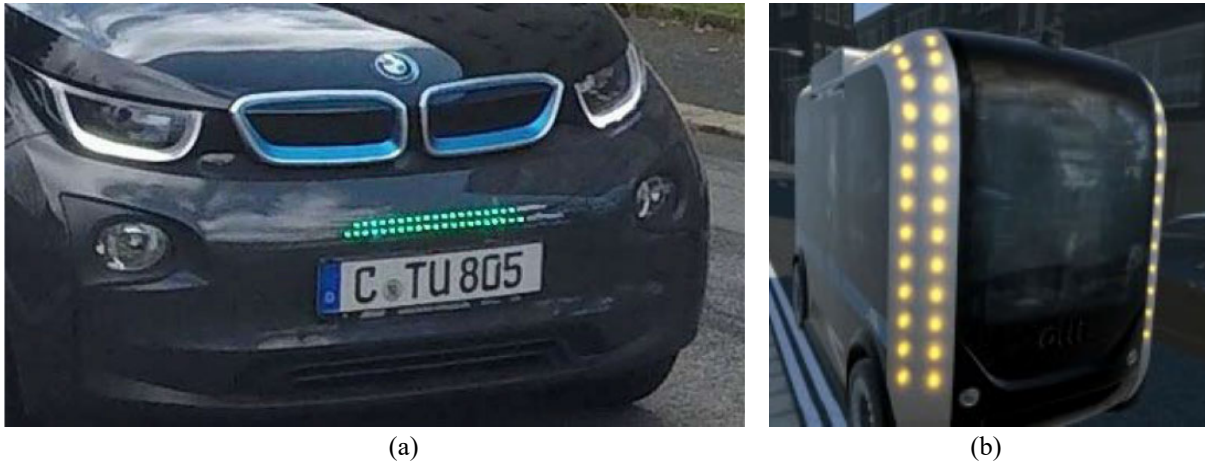


Fig. 2.13 Green frontal light for communicating the vehicle deceleration (a) [80], LEDs columns on the four corners of a vehicle for communicating the AV intentions through the different light patterns (b) [81].

with crossing the road when an AV with the light communication functions yielded to them. The results report that they felt safer and were more comfortable to cross the road when the light communication function was applied compared to when the function was not applied. Moreover, they reported that the communication function assisted them in making the crossing decision. Besides, the data about behaviors revealed that the participants were more hesitant to initiate the road-crossing in the absence of the light communication function.

Additionally, C. M. Chang *et al.* [82] investigated a concept of “eyes on a car,” that the vehicle headlamps served as the “eyes”. This concept works as a substitute for the lack of eye contact between drivers and pedestrians in the context of AVs. When the vehicle intends to yield, the headlamps turn and look at the pedestrian for indicating the vehicle awareness of the pedestrian and the yielding intention. Otherwise, the headlamps keep looking straight ahead. In the investigation, the participants were asked to play the role of the pedestrian and make the crossing decision before an approaching vehicle in a VR background. The results show that the majority of participants felt safer to cross before the vehicle equipped with “eyes on a car” as compared to the absence of this concept. In addition, the average time for participants to make the crossing decision was shorter in the presence of this concept compared to the absence.

Still, the contradictory findings on the effectiveness of light communication were noticed in few studies. A study on this point is from A. C. Hensch *et al.* [83], who evaluate an interface developed to communicate the AV mode and intentions. Their interface consisted of LED arrays positioned on the vehicle roof, which conveys three different messages via three colored light patterns. “Autonomous mode” was communicated via a constantly turquoise light, “Vehicle approaching” was communicated via a flashing turquoise light, and “Yielding” was communicated via a repeatedly sweeping turquoise light (see Fig. 2.14). In a parking area, random pedestrians interacted with an autonomous or manually driven vehicle both equipped with the interface and were interviewed immediately after the interaction. The pedestrians reported that the communication interface was intuitively incomprehensible and only partially trustworthy. They felt safer while interacting with a manually driven vehicle rather than an AV regardless of the existence of the interface. However, the majority of pedestrians agreed with the general usefulness of the interface for communicating the AV mode and intention.

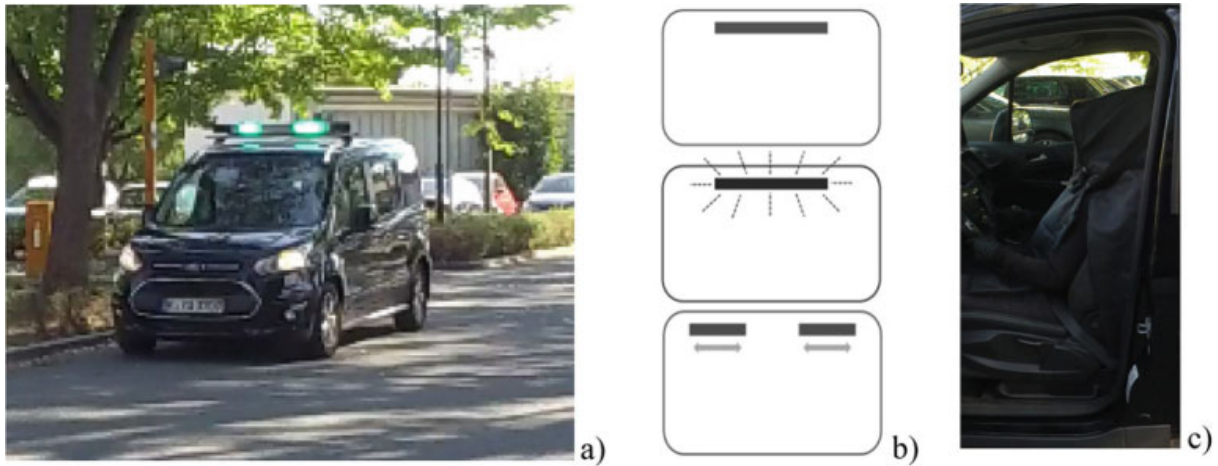


Fig. 2.14 Interface to communicate the AV mode and intentions positioned on the vehicle roof (a), Communication via three colored light patterns (b), Feature of AVs without human drivers pretended by a driver wearing a special seat suit (c) [83].

M. Clamann *et al.* [28] evaluated an intent communication interface by an measurement of pedestrian crossing decision time and by an interview. Their interface was a LED display positioned on the vehicle radiator grille, which displays a real-time vehicle speed, a silhouette of the walking pedestrian that communicates the road-crossing is allowed, and a crossed-out silhouette of the walking pedestrian that communicates the road-crossing is not allowed. Around a real-world unsignalized crosswalk, the pedestrians were asked to cross the road when an AV equipped with the communication interface was approaching. No effect of the interface on the pedestrian road-crossing was found, as evidenced by no significant difference of the crossing decision time between applying the interface or not. From the interviews, only a small number of pedestrians reported being influenced by the interface in their crossing decision-making. Nevertheless, a large number of pedestrians believed that the communication interface is needed on AVs. Notably, most of the pedestrians indicated that the distance from the vehicle to them and the vehicle speed determined their crossing decisions.

Considering that the vehicle movement-based cues including distance from the vehicle to the pedestrian and vehicle speed can influence the pedestrian decision-making in vehicle-pedestrian interactions, D. Dey *et al.* [84] carried out a controlled field study to understand the interdependent effects between the external communication interface and the vehicle movements. Their communication interface was a light bar integrated into the vehicle radiator grill. The autonomous cruising mode is presented by a fully lit bar in turquoise. The vehicle yielding intention is signaled by two lit segments in turquoise which slide repeatedly from the two edges to the middle of the light bar. In the field experiments, an AV exhibited one non-yielding behavior and three different yielding behaviors, consisting of gentle braking, early braking, and aggressive braking. Alongside, the vehicle yielding intention was communicated by using the communication interface and the pedestrian willingness of road-crossing was recorded. The results show that the communication interface helped to convince the pedestrians of the yielding intention, particularly when the vehicle speed is slow enough to not be an obvious threat, but still relatively fast to raise the doubt about whether the AV would stop. Importantly, it is pointed out that the pedestrians did not blindly trust the external communication interface. When there was a conflict between the information communicated



Fig. 2.15 Light projection used by Mercedes-Benz F 015 Luxury (a), Light strip embedded on the front of Renault EZ-GO (b), light band installed around Volvo 360c (c), Body display realized by Toyota Concept-I (d), “Eye contact” concept suggested in Jaguar Land Rover AV (e), “Smiling car” by Semcon (f).

by the interface and the vehicle movements, the pedestrians fell back to relying on the vehicle movements. Based on these findings, D. Dey *et al.* suggested that when explicit communication (communication interface) and implicit communication (movement-dynamics and kinematics) are in alignment and work in tandem, the communication of the AV yielding intention with pedestrians can be facilitated most effectively.

2.2.3.3 Practical Trial of Light Communication Concepts

To address the AV interaction problems, several light communication concepts have been

developed by automotive manufacturers (see Fig. 2.15). For instance, Mercedes-Benz F 015 luxury [64], equipped with LED displays on the front and rear, is able to show messages or pictograms to communicate with its surrounding road users. It is also equipped with a laser projection system which can project several lit arrows for showing its driving direction. In Renault's Ez-Go concept [85], a light strip embedded on the front of the vehicle which shows the specific light patterns for indicating the autonomous driving mode or informing pedestrians of whether to cross the road. Volvo calls for universal standards for AV communications. In its 360c AV concept [86], a 360-degree light band around the vehicle relies on the colored light patterns to communicate AV intentions with its surrounding road users. The Japanese automotive maker Toyota highlights the external communication concepts in its Concept-i AV [87]. AV intentions or warning messages are directly displayed on the vehicle body, which allows surrounding road users to read. Jaguar Land Rover [88] created an AV with "eyes" in order to reproduce the idea of eye contact between pedestrians and drivers. Additionally, Semcon suggests its "Smiling car" concept [65], which shows a facial expression "smile" on a frontal display for communicating AV intentions.

2.2.3.4 Authoritative Voices on AV Communications

As a new theme arising in recent years, the laws and regulations concerning the communication solutions between AVs and other road users are completely missing. Still, the transportation departments in different countries and the international standard developing organizations have given some authoritative guidelines and recommendations for the development of AV communication abilities.

U.S. Department of Transportation and National Highway Traffic Safety Administration mentioned in their *federal automated vehicles policy: Accelerating the next revolution in roadway safety* the necessities of signaling the intentions of highly automated vehicles to the environmental road users. The development of HMIs should be considered and take account of the HAV communication with pedestrians, conventional vehicles, and AVs [89].

"Furthermore, manufacturers and other entities should consider how HAVs (Highly Automated Vehicles) will signal intentions to the environment around the vehicle, including pedestrians, bicyclists, and other vehicles."

"Manufacturers and other entities should have a documented process for the assessment, testing, and validation of the vehicle HMI (Human-Machine Interface). Considerations should be made for the human driver, operator, occupant(s), and external actors with whom the HAV may have interactions (other vehicles, pedestrians, etc.). HMI design should also consider the need to communicate information to pedestrians, conventional vehicles, and automated vehicles regarding the HAV's state of operation relevant to the circumstance (e.g., whether the HAV system identified a pedestrian at an intersection and is yielding)."

*-Federal Automated Vehicles Policy: Accelerating the Next Revolution in Roadway Safety,
DOT&NHTSA*

In Europe, Germany Federal Ministry of Transportation and Digital Infrastructure in its Ethics Commission on Automated and Connected Vehicle reported that an HMI must be apparent at

any time for presenting which side is taking the control of the vehicle with the purpose of distinguishing the responsibility of either the ADS or the human driver in charge. This consideration hints the necessity of explicitly communicating the activation or deactivation of the autonomous driving mode [90].

“It must be possible to clearly distinguish whether a driverless system is being used or whether a driver retains accountability with the option of overruling the system. In the case of non-driverless systems, the human-machine interface must be designed such that at any time it is clearly regulated and apparent on which side the individual responsibilities lie, especially the responsibility for control. The distribution of responsibilities (and thus of accountability), for instance with regard to the time and access arrangements, should be documented and stored. This applies especially to the human-to-technology handover procedures. International standardization of the handover procedures and their documentation (logging) is to be sought in order to ensure the compatibility of the logging or documentation obligations as automotive and digital technologies increasingly cross national borders.”

*-Ethics Commission on Automated and Connected Vehicle,
Germany Federal Ministry of Transportation and Digital Infrastructure*

On the side of France, the white book which proposes the development guidelines for AVs edited by the national institute for research in digital science and technology describes that the HMI will become an essential component for AVs. This is because the information presented to drivers and passengers need to be hierarchized. These HMIs are dedicated to not only vehicle owners but also other road users who need to make necessary interactions with AVs [91].

“Avec les nouvelles fonctions intégrées à bord des véhicules, mais aussi le changement des modalités de conduite, des interfaces Humain-machine (IHM) spécifiques doivent être conçues pour les véhicules autonomes et connectés. L’IHM va devenir un élément essentiel du véhicule, car il sera impératif de hiérarchiser les informations présentées au conducteur ou à la conductrice, aux passagers et aux passagères, en fonction des priorités, des alarmes, des urgences... Ces nouvelles interfaces Humain-machine seront dédiées aux occupantes et occupants du véhicule, mais aussi aux autres usagères et usagers de la route avec qui des interactions seront désormais nécessaires. Elles seront conçues avec l’assistance d’ergonomes, d’expertes et d’experts des facteurs humains dans le domaine de la mobilité en général. Ces équipes devront en particulier étudier un point clé de l’interface humain-machine dans un VAC : l’arbitrage entre le pilotage automatique et le pilotage par le conducteur ou la conductrice, en fonction des contextes et des situations.”

*-Véhicules autonomes et connectés, les défis actuels et les voies de recherche (livre blanc),
INRIA*

Regarding international standard developing organizations, AV interactions and communications have also been discussed. In the *ISO/TR 23049:2018 Road Vehicles - Ergonomic aspects of external visual communication from automated vehicles to other road users*, it is mentioned that even though there are discussions about whether there is the need for external communications, it is important to start working on it. ISO recommends to use visual signals for external communications in order to help other road users navigate on the road. It is also recommended that the standardization, the learnability, and the signal numbers of external

communication systems should be focused on with the purpose of their implementation providing a positive impact on social acceptance and traffic safety [92].

“As AV systems enter the market, road users need to understand how to safely interact with these vehicles. This is particularly important when situations occur such as uncertainty of right-of-way involving road users of all types including AVs, pedestrians, bicyclists, drivers, and passengers. Although there is still some discussion about the need to provide external communication, it is important to start working on this concept. Within the minimum sound requirements for hybrid and electric vehicles (2016), the NHTSA requires non-internal combustion vehicles add an audible alert so that pedestrians with visual impairment can hear these vehicles at low speeds, full compliance by September 2019. Since any other audible signals would conflict with this regulated signal, visual signalling is recommended. Since the implementation of supplemental visual signalling on ADS-DVs may help other road users navigate traffic scenarios more easily, there is a need to investigate standardizing signals if they are to be used. Consistency across the automotive industry is needed to minimize potential road user confusion and establish societal trust with respect to ADS-DVs. This includes design considerations made for vehicles of different types and sizes.”

“It is recommended that if ADS-DVs have external visual communication systems, the communication should be standardized across the automotive industry. Learnability of these systems is a main focus, limiting the number of signals and ensuring they are distinct and salient yet not distractive, with the aim of their implementation providing a positive impact on societal acceptance and traffic safety.”

*-Road Vehicles-Ergonomic aspects of external visual communication
from automated vehicles to other road users,
ISO/TR 23049:2018*

2.2.3.5 Summary: Usage of Extended Automotive Signals for AV2P Light Communications

The AV interaction problems rise the new requirement for communications, especially between AVs and pedestrians. For providing AVs with communication abilities, automotive signal lights show great potential to be extended for signaling the AV status and intentions. For decades, lights have been used in traffic as an important communication modality for expressing messages [74]. The recent research works that compared different communication modalities also report that road users prefer to be notified about the AV intentions by light signals [49]. Furthermore, academics and industries have developed and tested several light communication functions and external HMIs, in which new possibilities of technologies and extended signals were demonstrated. For instance, light patterns, differing in motion and color, are one possible signal form based on the controllable LED arrays or matrix [62][81]. Pictograms, which are displayed on the vehicle or projected on the road, are also suggested to express AV intentions [63][64]. Moreover, in the research works which investigate the effects of AV2P communication functions, much evidence of their benefits was revealed, involving promoting the safe behaviors, contributing to the fast reaction, and improving the comfortable experience with regard to AVs [75][80][81]. Equally, the prototypes of light communication concepts demonstrate what they could look like on AVs and validate their feasibility [86]-[88]. As regards traffic regulations, there is actually no specific legal requirement for this emerging

subject. Nonetheless, the transportation and standardization authorities claimed many times the importance of developing an HMI for signaling the AV operating status and intentions, and the necessity of communicating this information with the pedestrians [89][91][92]. These proven benefits, these existing authoritative documents, along with the requirement for communications between AVs and pedestrians can support that automotive signals can be extended for providing pedestrians with not only the basic signalizations but also the advanced communication functions. It is expected that the AV2P communication functions can express the AV status and intentions to pedestrians for safe and efficient AV-P interactions.

2.2.4 Summary: Questions for Developing the Effective AV2P Light Communication Function

Although the AV2P light communication functions were acknowledged as the useful technological solutions for providing the required information of AV status and intentions, contradictory findings were revealed in few studies. Among them, some AV2P communication functions through the extended signals were regarded to be partially trustworthy and pedestrians still tend to stick to the implicit communication cues, namely vehicle speed and distance. These communication functions did not achieve their promise of facilitating the AV-pedestrian interactions [28][83][84], which reflects a considerable problematic that the AV2P light communication functions might lose their effectiveness. Based on our analysis, such ineffectiveness was likely due to the improper signal design and the unsuitable adaptation to the pedestrians' communication habits. In this early stage of developing light communication functions, a wide range of new signal forms is open. Without the standardized guidelines, academic and industrial designed their extended signals freely. Consequently, some improper signal designs might perform ineffectively as they were hard to be understood or the expressed message is meaningless from the perspective of the pedestrian. Besides, the reason for pedestrians to rely on the vehicle speed and distance rather than AV2P communication functions might be that the extended signal did not adapt to the pedestrian's communication habits in terms of activation timing and placing position. In vehicle-pedestrian interactions, pedestrians need to get useful information about vehicles in time and in place for letting them to make the decision. A retard in communicating the vehicle intention through the extended signal may force pedestrians to fall back to the implicit communications, e.g. vehicle speed and distance, to make their decision. A wrong place of showing the extended signals might distract pedestrians to get useful information. Correspondingly, we consider that *what are the appropriate signal designs for expressing the required messages and how the extended signal should be activated and placed* are two main questions for developing a user-centered AV2P light communication function. For resolving them, it seems important to further evaluate the performance of new signal designs in different forms and observe closely the vehicle-pedestrian interactions with particular attention to the communication mechanism. As regards the nature of this thesis, it should be pointed out that our further research works will not take place in the physical aspects, but consist of a matter of the new usage of extended automotive signals.

2.3 Suggested Messages and Available Signal Forms for AV2P Communication Functions

As regards the requirement for AV2P communications, it should firstly keep in mind that more messages to be communicated through extended signals do not mean the better. The overload of messages can lead to heavy fatigue for pedestrians and distraction for other road users. Expressing the required message through the appropriate signal designs is the right way to develop extended signals. According to our review, three most suggested messages, e.g. autonomous driving mode, vehicle yielding intention, and vehicle awareness of the pedestrian, along with the available signal forms, e.g. light pattern, pictogram, text, and anthropomorphism, are presented in the following.

2.3.1 Autonomous Driving Mode

The message about AV status, more precisely manually driving mode or autonomous driving mode, was as one of the key messages to be communicated by AVs. This is because knowing

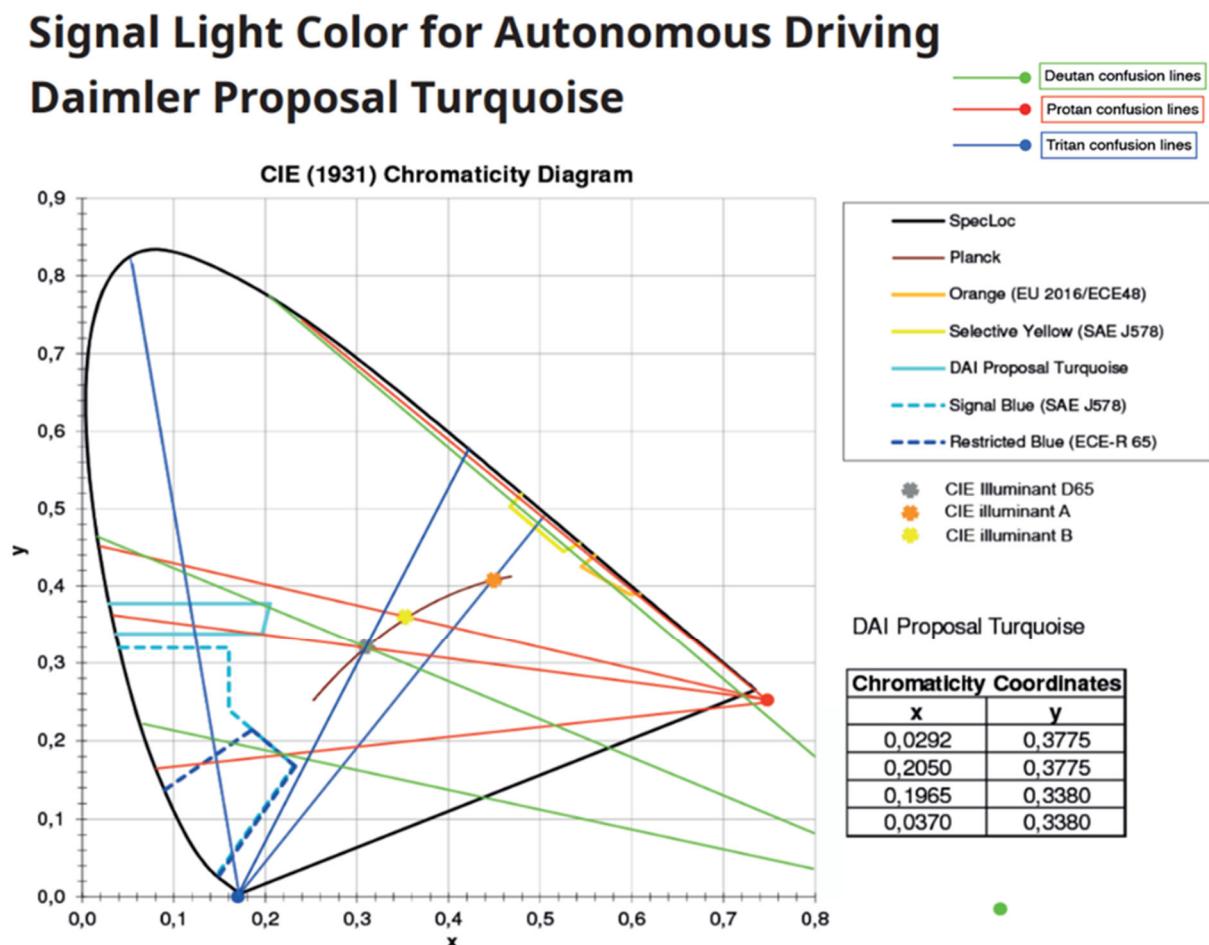






Fig. 2.16 CIE¹²xy (1931) chromaticity diagram depicting color regions defined by SAE and UNECE standards, and additional color region proposed by Daimler for labeling AVs [96].

Table 2.1 Comparison among turquoise, selective yellow, magenta, and mint-green for marking AVs [96]

colour	visibility central	visibility peripheral	discriminability normal / CVD	uniqueness	attractivity	rank order
 Turquoise	++	+++	+++ / ++	+++	+++	1
 Selective Yellow*	++	+	+++ / -	-	-	4
 Purple/Magenta	+	+++	+++ / -	+++	+/-	3
 Mint-Green	+++	+	+++ / -	++	+	2

CVD - colour vision deficiency

* already present as signal on vehicle

+/- positive/negative evaluation

the type of vehicle, especially in the transition period where vehicles in the different automation levels and manually driven vehicles are mixed on the road, is helpful for pedestrians to become vigilant with regard to AV specific driving ability and behaviors. H. Tiesler-Wittig [93] suggested that the operation of ADS should be indicated, in order to inform the surrounding road users that AVs might behave differently from manually driven vehicles. This is in line with L. Müller *et al.* [94], arguing that problems could raise due to the wrong identification of AV driving mode. Road users, who wrongly distinguish AVs and manually driven vehicles, might have wrong expectation on these vehicles. The expectation on vehicles has been found to have a large effect on road users' decision-making and behaviors [95]. Another reason for communicating the AV status is relevant to the responsibility, as reported by the ethics commission of Germany Federal Ministry of Transport and Digital Infrastructure [90]. In the case of accidents, which side, whether the ADS or human driver, was in charge of the vehicle control is necessary information for distinguishing the responsibility.

For communicating this message, the widely proposed signal forms consist of a steady light and a lit text of "Autonomous Vehicle/Driving" in a dedicated color. The light color for AVs which is mostly acceptable is the blue-green, namely cyan or turquoise. On the side of academics, A. Werner [96] who compared the turquoise, the selective yellow, the magenta, and the mint green, rated the turquoise as the suitable color for marking AVs. This is on account of its better performance in terms of visibility central, visibility peripheral, discriminability normal, uniqueness, as well as attractiveness (see Fig. 2.16 and Table 2.1). Besides, D. Dey *et al.* [97] tested green, cyan, and red eHMIs by online surveys and concluded that the participants regarded the cyan as "a neutral color" for communicating a yielding intention. On the side of automotive manufacturers, Daimler and Volvo [98][86] updated their AV signal lamps, which allows them to emit the turquoise light for indicating the autonomous driving mode. On the side

of standard developing originations, SAE J3134 proposed to communicate the ADS activation status by switching on and off ADS maker lamps by using the blue-green color.

2.3.2 AV Yielding Intention

A central element of information to be communicated by vehicles is its maneuvers, for example deceleration or acceleration that changes gaps between vehicles and the other road users. It is identified that the communication of vehicle maneuvers supports other road users to predict the current and next vehicle behavior. There, other road users can make the correct decision in the interactions [99]- [105]. By adapting to AV2P communications, the deceleration or acceleration can be interpreted as the vehicle yielding intention. This message can be supposed as one message in need for facilitating AV-pedestrian interactions. Precisely, the suggestion of communicating the vehicle yielding intention can be heard from the U.S. transportation department in its federal automated vehicles policy [89]. In this document, it is highlighted that whether the AV identifies and yields to a pedestrian should be considered as the information to be clarified. Similarly, SAE J3134 [77] supports a practice through dedicated ADS signal lamps to communicate the message about AV yielding intention.

A big flexibility of signal forms exists for expressing this message in AV2P communications. SAE J3134 proposed to give the meaning of AV yielding intention to new light patterns, such as a flashing light or a sweeping light in blue-green [77]. Without the consensus, other light patterns, differing in motion and color, were invented by researchers with the purpose of expressing the yielding intention, for example a repeated light in amber expanding from the middle to the two sides of LED arrays [62] or a pulse light in cyan with the increase and decrease of light brightness shown by a light bar [97]. Otherwise, signals in the form of pictograms, differing in figure, symbol, and color, were designed for communicating the vehicle yielding intention and have been evaluated in many research works [106]-[110]. In these pictograms, it is notable that a figure of the walking pedestrian and an arrow symbol were the usual composing elements, which were selected for signifying the AV yielding intention. Evidently, texts are another available signal form that can be used to express the vehicle yielding intention [107][108][111][112]. As far as the text is concerned, “Walk”, “Go”, “Brake”, “Stop” or their synonyms were largely suggested to informing pedestrians of the AV yielding intention.

2.3.3 AV Awareness of the Pedestrian

In several situations especially in low speed vehicle-pedestrian interactions, a driver’s responding to the pedestrian gaze for establishing the eye contact or a driver’s head orientation toward the pedestrian are taken into account as the way to communicate the driver awareness of the pedestrian [56][57][58]. As regards AVs, this communication will be no longer available due to the absence of human drivers. For road safety, it would be required to replace this behavioral communication by technical means which communicate the AV awareness of the pedestrian. N. Merat *et al.* [49] addressed what externally presented information do the VRUs wish while interacting with AVs. They found that the pedestrians preferred to receive the message about whether AVs have detected themselves, namely awareness of the pedestrian.

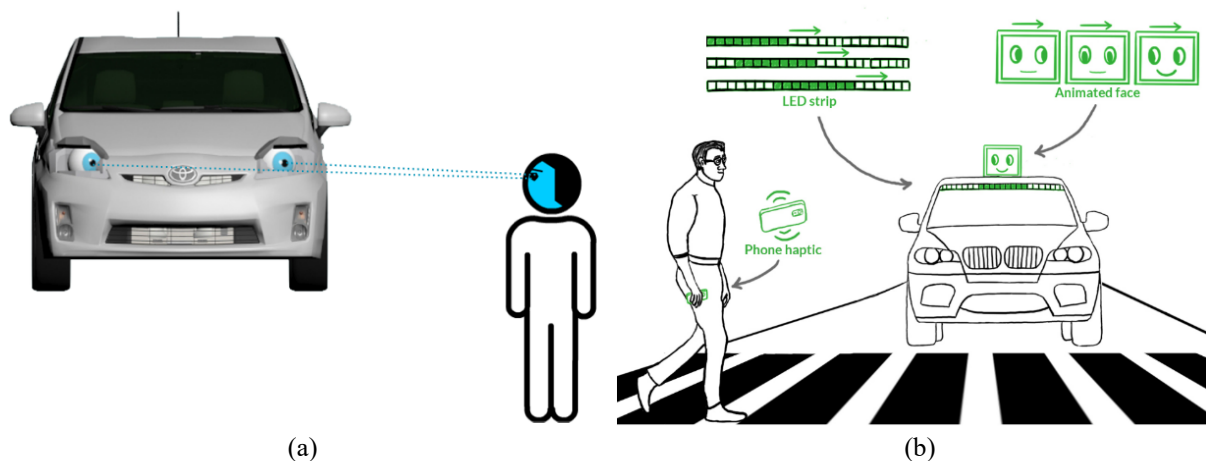


Fig. 2.17 Communication of the AV awareness of the pedestrian in the form of anthropomorphism: two moving eyes taking place of the headlamps (a) [82], a display device showing an animated face with oscillating eyes (b) [75].

For communicating this message, a distinctive signal form recommended by academics and industries is the anthropomorphism which means to imitate the eye contact between the driver and the pedestrian. For example, C. M. Chang *et al.* [82] imagined an AV with two moving eyes which take place of the traditional headlamps. When the AV detected a pedestrian, the eyes will turn to look at the pedestrian in order to tell the pedestrian that (s)he has been seen (see Fig. 2.17a). The similar solution [75] can be a display device showing an animated face with oscillating eyes (see Fig. 2.17b). Apart from the anthropomorphism, light patterns are equally available for indicating the AV awareness of the pedestrian. Regarding the concept of AutonoMI, a segment of LED array closest to the pedestrian lights up for acknowledging that the pedestrian has been detected. When the pedestrian cross before the AV, the lit segment follows the pedestrian to express that he or she has been seen always [113]. Besides, in spite of being rarely proposed, pictograms own the possibility to express the AV awareness of the pedestrian by using an eye figure [106].

On the topic of what kind of communication is needed as regards ADS, *Groupe de Travail Bruxelles (GTB)* which works on the standardization of automotive lights and signal lights suggested that the safety signals for AVs can be realized step by step with respect to the signal complexity [114]. In the first step, the message to be communicated is the autonomous driving mode. By switching on and off a dedicated signal light, it is simple to indicate whether the ADS is active or inactive (see Fig. 2.18). It is expected that this signal can already tell other road users to take care with AVs. From the point of view of GTB, signaling the autonomous driving mode is mandatory and should be realized in a short term. In the second step, it is suggested that modulated signals, such as flashing, can be relied on to communicate ADS intentions, such as AV yielding intention and starting driving intention. These signals for expressing ADS intentions are optional or mandatory, which should be realized in a mid term. In the next step, more signals can be added into the automotive signalization for communicating more complex messages, such as perception of environments and cooperation capacities. These signals are totally optional and can be realized in a long term.

- Single vs. multi-step communication
- What kind of communication is needed for ADS?

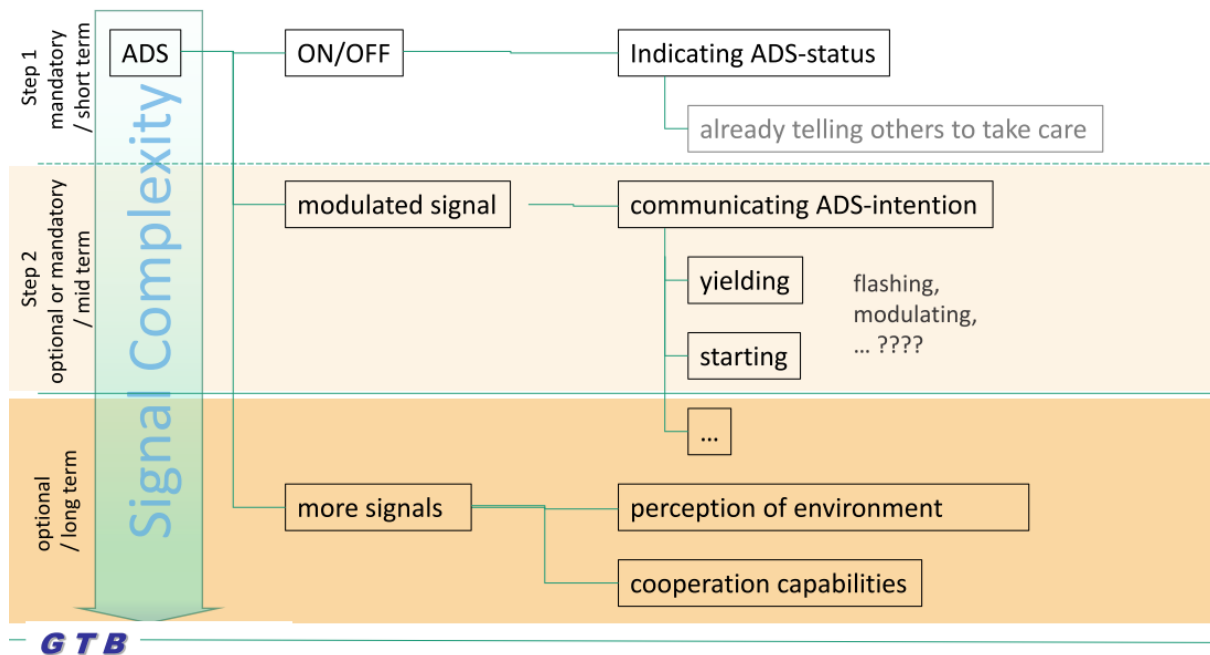


Fig. 2.18 GTB multi-step development of safety signals for AVs depending on the complexity [114].

The suggestions from the academics, the industries, and the standard developing organizations mainly focused on three messages for AV2P communications, consisting of the autonomous driving mode, the AV yielding intention, and the AV awareness of the pedestrians. As regards the communication of autonomous driving mode, it seems like an agreement of using ON/OFF blue-green light based on existing automotive vehicle lamps or a new lamp is established among the stakeholders [83][84][98][114][115]. As regards the messages about AV yielding intention and awareness of the pedestrian, it could be supposed that the latter one may not be truly needed in the case where the former one has been expressed. This is because the AV yielding intention which was expressed to a pedestrian through some signals already contains the meaning that the AV has been aware of the pedestrian. As far as the available signal forms, consisting of light pattern, the pictogram, the text, as well as the anthropomorphism, a big number of extended signals in the forms of them were designed for AV2P communications. In the related research works, the positive effects of these signal designs have been demonstrated in terms of promoting the recognition of vehicle intention and improving the perceived safety towards the vehicle [62][63][79]. However, regarding the further question on what are the appropriate signal designs for the most effective AV2P communications, there has been no consensus yet [116]. In any case, this question about signal designs should be answered with the purpose of developing AV2P communication functions. Thereby, many investigations have been carried out to compare the performance of different signal designs within the similar form and across the different forms.



Fig. 2.19 Comparison among three light patterns proposed to communicate the vehicle yielding intention: steady blue-green light (a), flashing blue-green light (a), sweeping blue-green light (b) [117].

2.3.4 Comparison within the Similar Signal Form

A study involving three light patterns is from M. Faas *et al.* [117], who evaluated an interface developed to communicate the AV yielding intention, in terms of crossing initiation time, crossing duration time, user experience, learnability, and likeability. Their interface consists of a LED light strip mounted on the top of the vehicle windshield. The yielding intention was suggested to be communicated through a steady light, a flashing light, and a sweeping light in blue-green (see Fig. 2.19). In the Wizard-of-Oz field experiments, the participants, who were tasked with crossing an unsignalized intersection, saw each of the three suggested light patterns demonstrated by an approaching AV. The results show that the participants started crossing sooner with the flashing light than with the sweeping light, and there was no significant difference of crossing initiation time between the flashing lighting and the steady light. As far as the user experience, the flashing light was rated higher than the sweeping light in terms of learnability and likeability.

Using the online surveys, J. Zhang *et al.* [118] evaluated their AV “Intention indicator”, consisting of an RGB LED strip positioned on the two vehicle front doors and hood. The indicator was developed to communicate five vehicle intentions by the different colored light patterns differing in motion and color. “Vehicle slowing-down”, “Waiting”, “Planning to go”, “Starting to go”, and “Going” intentions are signaled respectively by a forward-moving white light, a slow backward-moving green light, a static green light, a flashing white light, and a slow backward-moving red light. The participants, who watched the videos of an AV mounted with the intention indicator, were required to identify the vehicle intention and rate the effectiveness of the different motions and colors. The results showed that “Planning to go” was confused with “Waiting”. “Starting to go” was confused with “going”. The participants preferred to use green color to indicate “Starting to go” and “Going”. They preferred to use red color to indicate “Slowing-down” and “Waiting.” In addition, the forward-moving light was preferred for indicating a moving or accelerating vehicle, and the back-moving light was preferred for indicating a stopping or decelerating vehicle.

M. Hamm *et al.* [119] assessed a series of pictograms composed of different figures and symbols by measuring the reaction time and the interpretation correctness. As one available signal form for AV2P communications, these pictograms were designed for the vehicle yielding intention, the turning intention, and the AV detection of the pedestrian. In their laboratory

investigation, the tested pictograms were shown on two display devices mounted on the two sides of the vehicle bumper. The participants were asked to stand before a vehicle, push the button if they can correlate their interpretations on the signal meaning with one of the given options. The results point out that a shorter reaction time and a higher rate of interpretation correctness were linked with the pictograms which are two dimensional, easy to understand, not complex, and dynamic.

In the monitor-based online survey of P. Bazilinskyy *et al.* [111], four signals in the form of text, “WALK”, “DON’T WALK”, “STOP”, and “WON’T STOP”, in green, red, and white colors used to communicate whether the vehicle yields to the pedestrian were evaluated in terms of perceived safety. From the point of view of a pedestrian, “WALK” and “DON’T WALK” were categorized as egocentric messages, whereas “STOP”, and “WON’T STOP” were categorized as allocentric messages. In the online survey, the participants saw the photos of a vehicle overlaid with the tested texts positioned on the vehicle license plate and reported if they would feel safe, unsafe, or unsure to cross before the vehicle. The results show that the participants felt safer to cross before the vehicle for the egocentric “WALK” than for the allocentric “WILL STOP”. They found the egocentric “DON’T WALK” to be less ambiguous than the allocentric “WON’T STOP”. Additionally, it is pointed out that the text was more dominant than the color in expressing messages.

2.3.5 Comparison across the Different Signal Forms

S. Stadler *et al.* [120] investigated the efficiency, the effectiveness and the satisfaction of ten extended signals for AV2P communications in a VR-based investigation. In their setup, the participants played the role of the pedestrian who intends to cross the road before an approaching AV. An AV showed the extended signals for communicating whether it is safe for pedestrians to cross the road. A controlled group in which the AV did not show the extended signals was set as well. For the extended signals to be investigated, they are six pictograms respectively composed of a green walking pedestrian figure, a red standing pedestrian figure, arrow symbols, a red raised hand figure, a green check symbol, and a red X symbol, two light bands in green and red, and two double light points in green and red (see Fig. 2.20). By measuring the pedestrian crossing decision time and decision error, the results show that the participants have a significantly shorter crossing decision time and less crossing decision error when facing the AV showing the extended signals compared to the controlled group. In the comparisons among the signals, the green check symbol, the red X symbol, the light bands in green and red were less effective, as the crossing decision error was found with them. The

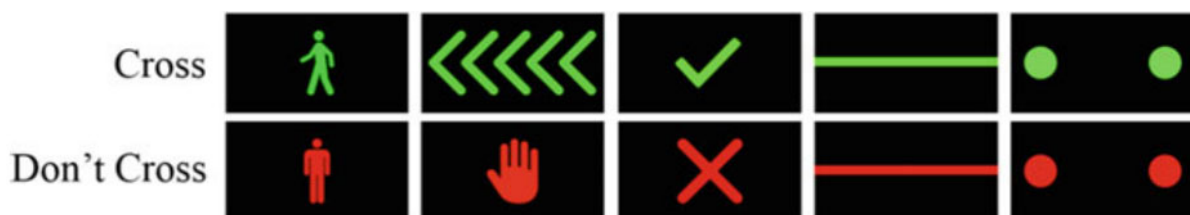


Fig. 2.20 Comparisons among six pictograms respectively composed of a green walking pedestrian figure, a red standing pedestrian figure, arrow symbols, a red raised hand figure, a green check symbol, and a red X symbol, two light bands in green and red, and two double light points in green and red [120].

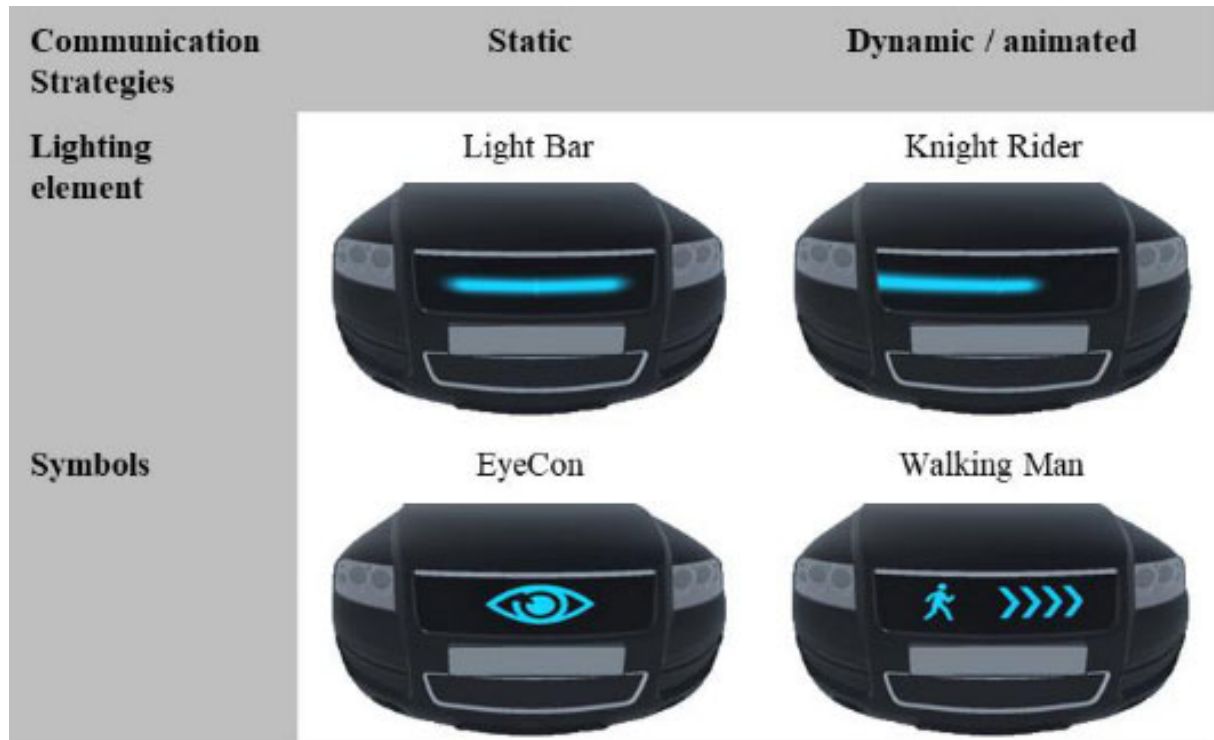


Fig. 2.21 Comparison among a static light bar, a dynamic “Knight Rider” light, a static eye symbol, and a dynamic walk pedestrian silhouette associated with arrow symbols [106].

qualitative measurement of the satisfaction shows that the participants were satisfied with the extended signals. The highest user satisfaction was rated for the arrow symbols and the red raised hand figure, as they are regarded as the most detectable and comprehensible. The lowest user satisfaction was given to the light bands in green and red.

In the VR-based simulation experiment of I. Othersen *et al.* [106], four signal designs, including a static light bar, a dynamic “Knight Rider” light, a static eye symbol, and a dynamic walking pedestrian silhouette associated with arrow symbols, displayed on a screen installed on the vehicle radiator grill were evaluated in terms of pedestrian crossing initiation time and user experience (see Fig. 2.21). The static designs intend to express a message of “I have seen you” and the dynamic designs intend to express “You may now cross the road in front of me”. It is found that the participants crossed the road sooner when the signal was presented on the vehicle as compared to no presence of the signal. Interestingly, with the presence of the signal, 28% of the pedestrians crossed the road earlier than the vehicle came to a full stop. Comparatively, only 9% of the pedestrians made the same thing with no presence of the signal. In the comparisons among the four signal designs, the effect on accelerating the crossing initiation time was less effective for the two static designs. About the user experience, the dynamic walking pedestrian silhouette associated with the arrow symbols was reported as the highest in terms of understandabilities and perceptibility. The two static designs were found to be uninformative and unrelated to their desired meaning.

S. Deb *et al.* [109] evaluated in a VR-based investigation several visual and audible signals, with regard to their influence on AV-pedestrian interactions. The visual signals include a flashing text of “BRAKING” in green, an animated pedestrian silhouette of the in white, as well

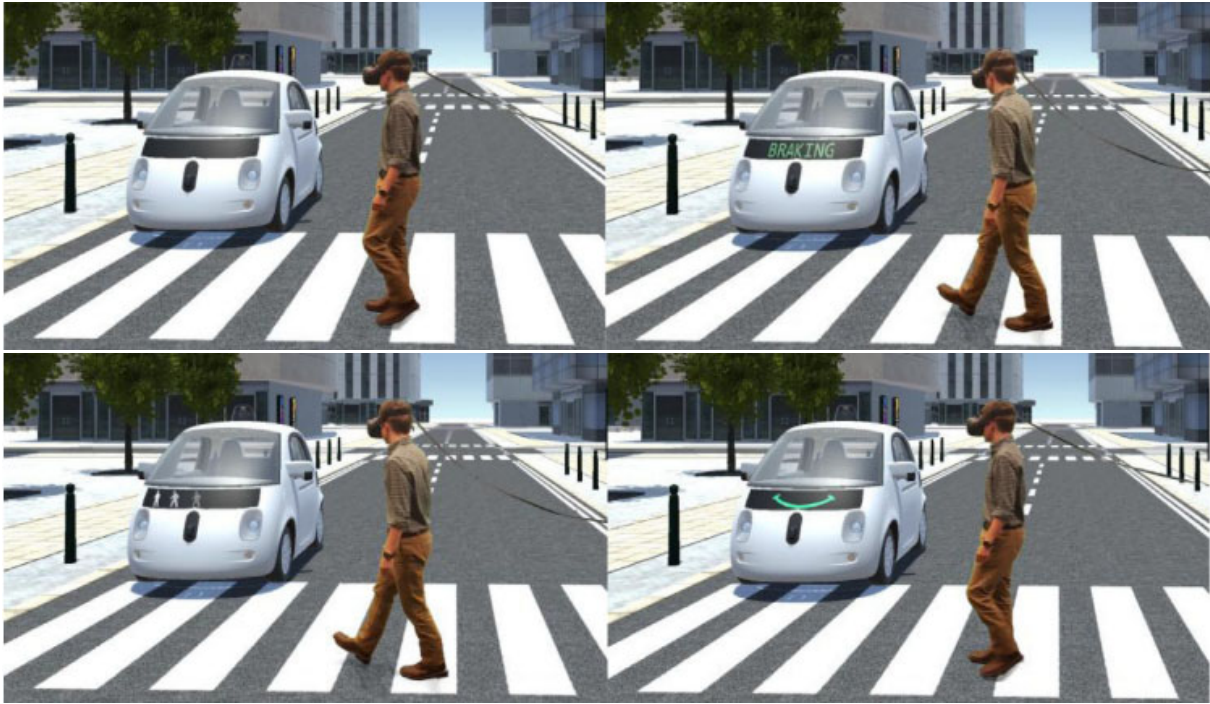


Fig. 2.22 No signal, a flashing text of “BRAKING” in green, an animated pedestrian silhouette in white, and a flashing smile in green, compared in the VR-based investigation [109].

as a flashing smile in green. The audible signals include a horn sound, a piece of music, and a verbal message speaking “safe to cross” (see Fig. 2.22). The participants were tasked with crossing in front of an AV which is yielding to them around an unsignalized crosswalk. By rating the perceived safety, it is found that the participants felt safer while interacting with vehicles mounted with these signals as compared to no signal on the vehicle. More precisely, the flashing text of “BRAKING” and the animated pedestrian silhouette were the most favored visual signals. The verbal message was the most favored audible signal. Additionally, as far as the crossing time is concerned, the music and the verbal message led to the shortest crossing time, whereas the horn sound led to the longest crossing time.

In another VR-based study, C. R. Hudson *et al.* [112] evaluated a set of signal designs based on an interface developed to support pedestrians in their interactions with AVs. Their interface consisted of a LED display positioned on the vehicle hood and a speaker. In the experiments, the LED display showed four visual signals, including a green text of “WALK”, a white walking pedestrian silhouette, a red raised hand, and a STOP sign. The speaker played either music or a verbal message of “safe to cross”. The participants experienced the street-crossing scenario where an AV equipped with the interface is approaching and were asked to rate their preference with respect to each signal design. The results show that the interface was more preferred than the baseline where the interface was not equipped on the AV. Besides, the text of “WALK” and the STOP sign were the most preferred visual signal designs, whereas the verbal message of “safe to cross” was the most preferred audio signal.

The comparison of extended signals across different forms which address children’s needs was the focusing point in the study of V. Charisi *et al.* [121]. The children aged from 7 to 10 years old were selected for their tests. They were tasked with responding to whether AVs equipped

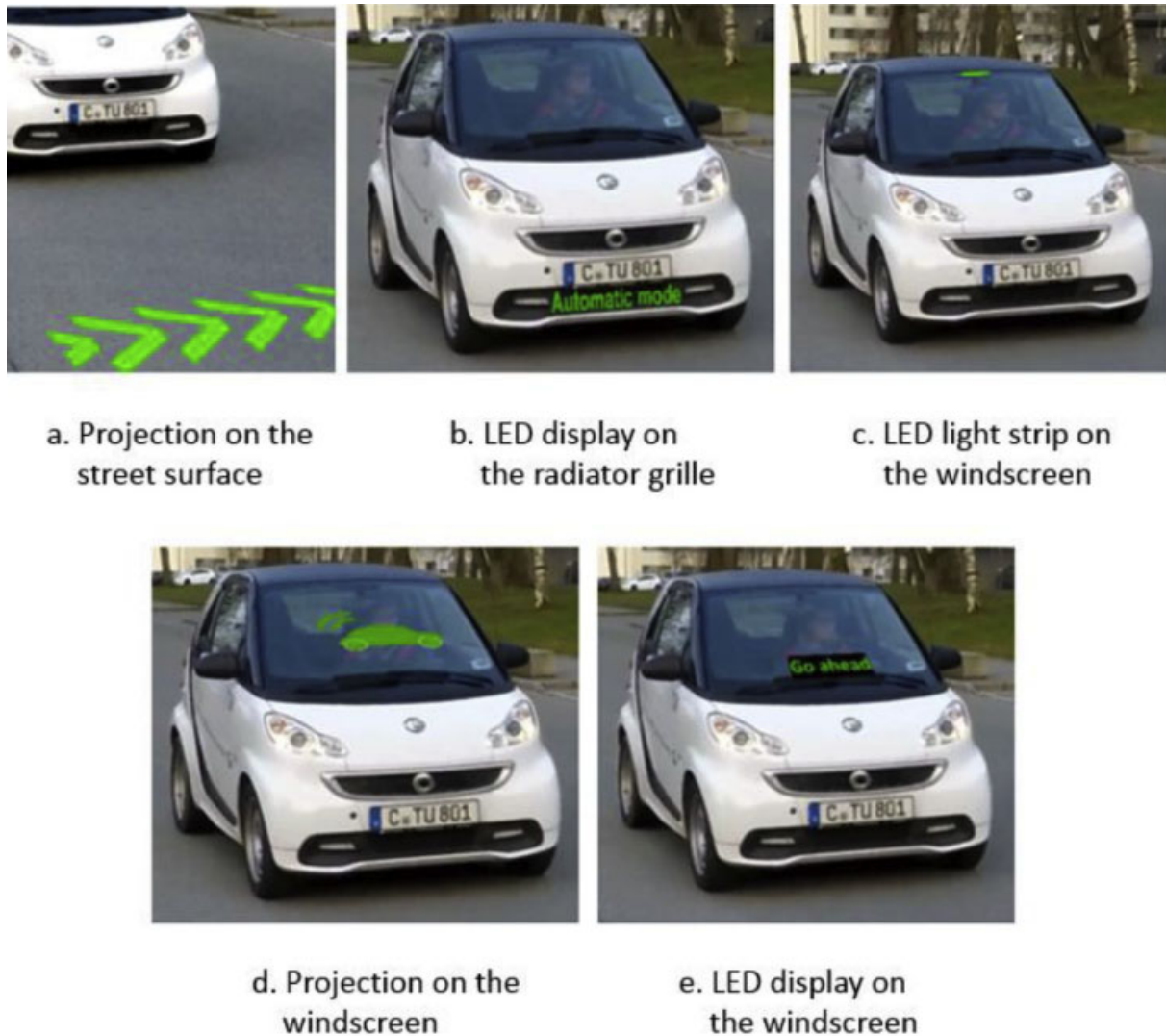


Fig. 2.23 Communication interfaces differing in technology, location, message coding, and content type, compared by the augmented real-world videos [108].

with different signal designs will yield to them in a questionnaire. The signal designs include traffic lights, traffic signs, projected crosswalks, drawings of “GO” and “STOP” placards, pedestrian figures, headlights, LED light strips, and vehicle anthropomorphism, which are used to clarify the vehicle yielding intention. The results show that the familiar signals, namely traffic lights and traffic signs, and the signal designs based on present mental models, namely drawings of “GO” or “STOP” placards, were the most accurately responded to. On the contrary, the vehicle anthropomorphism was the least responded to. Moreover, the standard traffic colors (red, green, and amber) were more accurately responded to than the colors which are not commonly used in traffic (purple, dark blue, and light blue).

C. Ackermann *et al.* [108] studied four parameters of their communication interfaces in terms of intuitiveness, comprehensibility, recognizability, ambiguousness, and interaction comfort. The interfaces differ in technology (projection; LED display; LED light strip), location (windshield; radiator grille; street surface), message coding (pictorial: car icon, directional arrows; textual: “Automatic mode” and “Go ahead”), and content type (vehicle mode

information; advice to pedestrians). The participants saw from the point of view of a pedestrian the augmented real-world videos of an approaching AV equipped with one of the different interfaces and were asked to rate them (see Fig. 2.23). In terms of intuitiveness and comprehensibility, the LED light strip got the lowest rating. In terms of recognizability, the projection was rated better than the LED display. The advice to pedestrians was rated better than the vehicle mode information, regardless of message coding. Besides, in terms of ambiguousness, the advice to pedestrians was rated better than the vehicle mode information. The pictorial coding was rated worse than the textual coding. In terms of interaction comfort, the projection and the advice to pedestrians were respectively rated better than the LED display and the vehicle mode information.

Moreover, L. Fridman *et al.* [107] evaluated a series of signal designs by augmented real-world photos. Their signal designs differ in location (windshield; headlights; fog lights; directional signals; radiator grille; bumper; road surface), text (“WALK”; “DON’T WALK”; “GO”; “STOP”; “CAR STOPS”), icon (walking pedestrian silhouette; raised hand; STOP traffic sign; pedestrian sign; arrows; dotted circle), and light color (green; red; yellow; white). The test participants were tasked with deciding if it was safe to cross the road after watching the augmented photos which show the signal designs on a vehicle. As regards the signals designed for communicating that the crossing is safe, the results show that the green walking pedestrian silhouette displayed on the windshield, the green text of “WALK” displayed on the windshield, the green directional arrows projected on the road surface, and the green text of “WALK” projected on the road surface were the most accurately responded to. As regards the signals designed for communicating that the crossing is not safe, the yellow raised hand and the text of “DON’T WALK” on the windshield were the most accurately responded to.

M. Hochman *et al.* [123] carried out a monitor-based investigation to test eight signal designs based on a display device installed on the vehicle roof. The eight signal designs are in the forms of pictograms and texts, with two conveying advice of crossing in the green background, two conveying advice of stopping in the red background, two stating the vehicle information about



Fig. 2.24 Pictograms and tests differing in content type and background color, compared in the monitor-based investigation [123].

slowing-down in the green background, and two stating the vehicle information about driving in the red background (see Fig. 2.24). The participants were tasked with watching the videos in which an approaching AV displays the tested signal and making the crossing decisions. The results in terms of crossing decision error show that, in the green background, the pictogram and the text designed for stating the vehicle information about slowing-down performed worse than those designed for convey advice of crossing. In the red background, no difference was found between the pictogram and the text stating the vehicle information about driving and those conveying advice of stopping. In addition, it is observed that the participants tended to look at the display device before making their decisions.

2.3.6 Summary: Lack of Studies on the Understandability of Extended Signals

For having effective AV2P communication functions, what are the appropriate signal designs used for expressing AV status and intentions has been hotly discussed. To study this question, a large number of signal designs in the forms of texts, light patterns, pictograms, and anthropomorphism were proposed and their performance has been evaluated. In the related research works, it is found that the performance of the texts was generally well in the AV2P communications [108][109][112][122]. However, facing thousands of languages used worldwide, it should be known that this signal form would be restricted due to the requirement of global standardization. Regarding the anthropomorphism, the number of related research work was currently little. Still, the insights found from them show a propensity that pedestrians are not greatly favored with this signal form. This may be linked to the fact that the present mental models of pedestrians are not used to interpret this unfamiliar signal form in traffic [75][121]. In consequence, it would be better to focus on light patterns and pictograms, as two available signal forms for AV2P communication functions. In the current traffic system, light patterns have been already used in traffic lights and pictograms have also been widely used in traffic signs. Moreover, both of these two signal forms are conspicuous and legible from a long distance which are of interest for explicit AV2P communications.

In the research works which compared signal designs in the different forms, a wide range of subjective metrics were used to evaluate their performance, such as perceived safety, preference, comfort, perceptibility, and learnability (see Fig. 2.25). The results obtained based on them provided some interesting personal opinions of test participants on the evaluated signal designs. Besides, the pedestrian crossing initiation time and the pedestrian crossing decision time have been the usual indicators to objectively evaluate the signal designs in the aspect of pedestrian behaviors [28][82][106][109][117][120][124]. Notably, it is observed that compared to the signal designs composed of the well-known features, the abstract ones performed badly in accelerating the crossing decision-making and could even lead to the crossing decision error [106][120]. This suggests that the understandability of signals is a key factor that determines the decision of pedestrian behaviors through AV2P communications, whereas it has not been deeply studied [83][106][108][111]. Although the related research works briefly investigated the understandability by the scaled rating of clarity or comprehensibility [83][108][111], their results can hardly provide explanations on why some kinds of signal designs lost their promised functions in AV2P communications. For ensuring the effectiveness of AV2P communication

functions through extended signals, it is logical that the proposed signal designs must be understandable. Therefore, it would be necessary to include particular studies on investigating as what exactly pedestrians understand extended signals in the different forms. It is expected that the studies on the understandability would provide some useful evidence for the selection of appropriate signal designs used for AV2P communications.

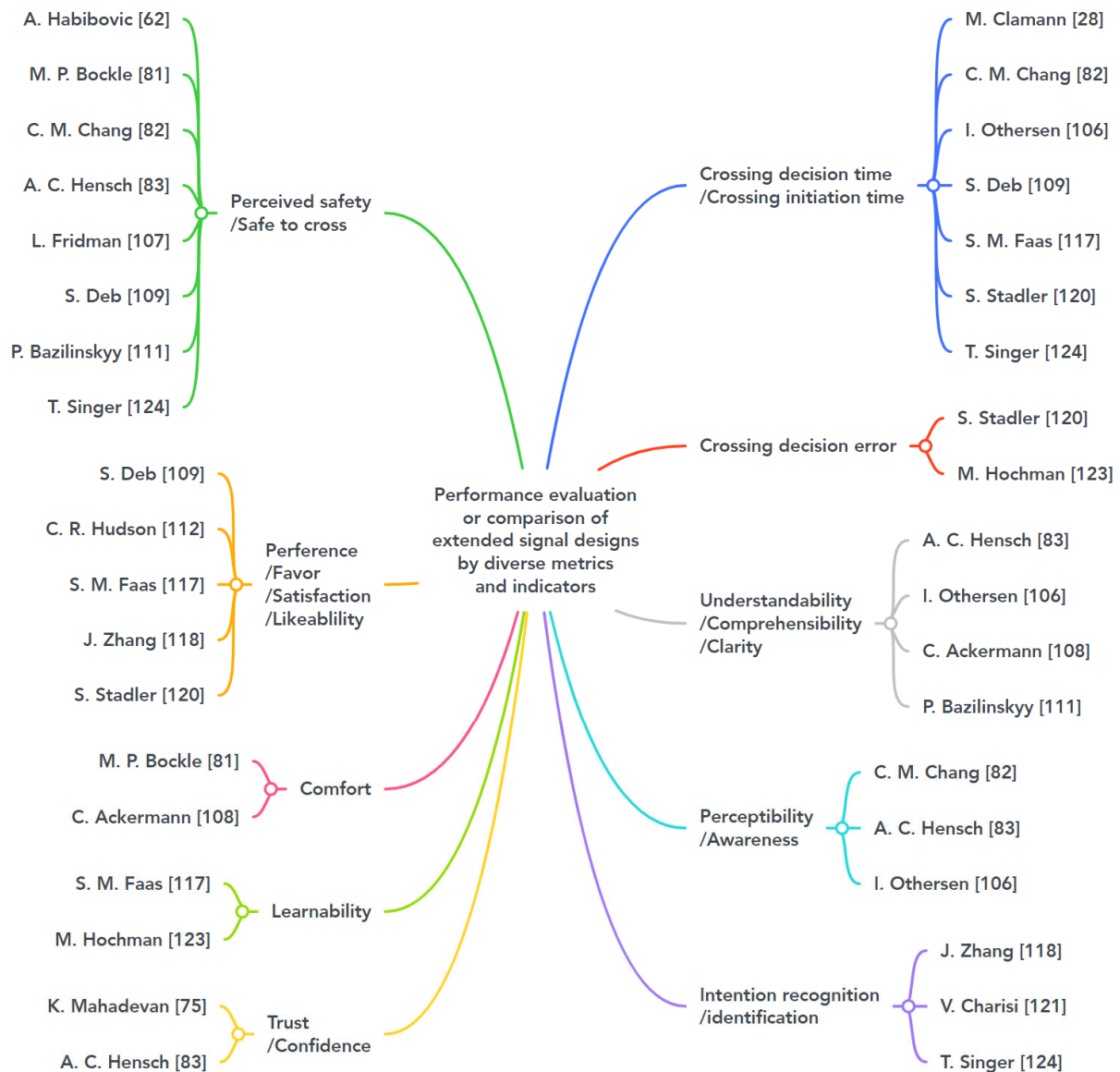


Fig. 2.25 Summary of research works which evaluate or compare the performance of extended signals designs in the different forms by diverse metrics and indicators.

2.4 Communications in the Vehicle-Pedestrian Interactions

The day-to-day traffic interactions are principally under the constraints of official laws and regulations. In addition, many other factors are found to influence the interactions among road users, including demographics, road conditions, social norms, and traffic features [35][36]. Besides, the communications play an essential role in exchanging information in the interactions. The lack of communication or miscommunication could result in irritations, traffic conflicts, and even accidents among road users [59] [125]. In particular, pedestrians heavily rely on the communications through implicit, explicit, and behavioral channels to interact with vehicles.

2.4.1 Implicit Communications

Implicit communications can be defined as the status of road actors' own in the relevant context, depending on which the observer can make inferences about their intentions. This definition was adapted from the work of A. Schmidt [126], and contextualized for vehicle-pedestrian interactions. The typical examples are the vehicle speed and the distance from the vehicle to the pedestrian. Pedestrians need to consider these implicit communication cues for coordinating the mutual actions with vehicles.

F. Schneemann and I. Gohl [100] carried out a study with real-life field experiments to analyze vehicle-pedestrian interactions around crosswalks. The obtained results show a significant influence of vehicle speed on the pedestrian decision-making process. In 75% of the situations, the pedestrians stated that they perceived a clear deceleration of vehicle speed prior to making their crossing decision. This was true for the vehicle-pedestrian interactions around the crosswalk in both 30 km/h and 50 km/h zones. Besides, it is pointed out that in the 50 km/h zone, most of the pedestrians gazed at the approaching vehicle for judging if the driver made a yielding decision, whereas in the 30 km/h zone, the pedestrians searched the driver's eyes.

A. Varhelyi [104] launched a case study on an unsignalized mid-block crosswalk by randomly measuring the vehicle speed and video recording the vehicle-pedestrian interactions. It is observed that three out of four drivers maintained the same vehicle speed or even accelerate the vehicle for not yielding to pedestrians. One out of four drivers slowed down or braked the vehicle for yielding to pedestrians. The further observation reveals that maintaining the high vehicle speed or exceeding the speed limit is a signal sent from drivers to show that they do not intend to give way to pedestrians. Overall, an interpretation of "signaling by speed" was given.

Additional insights about the vehicle speed were given by A. Rasouli *et al.* [127]. From a database which contains the video samples of vehicle-pedestrian interactions, they distinguished and labeled the notable driver (vehicle) and pedestrian behaviors (see Fig. 2.26). It is noticed that the pedestrian slowing-down or stopping behaviors could be the indicator of noticing the vehicle approaching and non-yielding behaviors. Besides, in the majority of cases, the pedestrians crossed the road when the drivers acknowledged their yielding intention by slowing down or stopping the vehicle.

A basic concept that influences the pedestrian crossing decision is the gap acceptance. It signifies how much gap the pedestrian considers is safe to cross the road when interacting

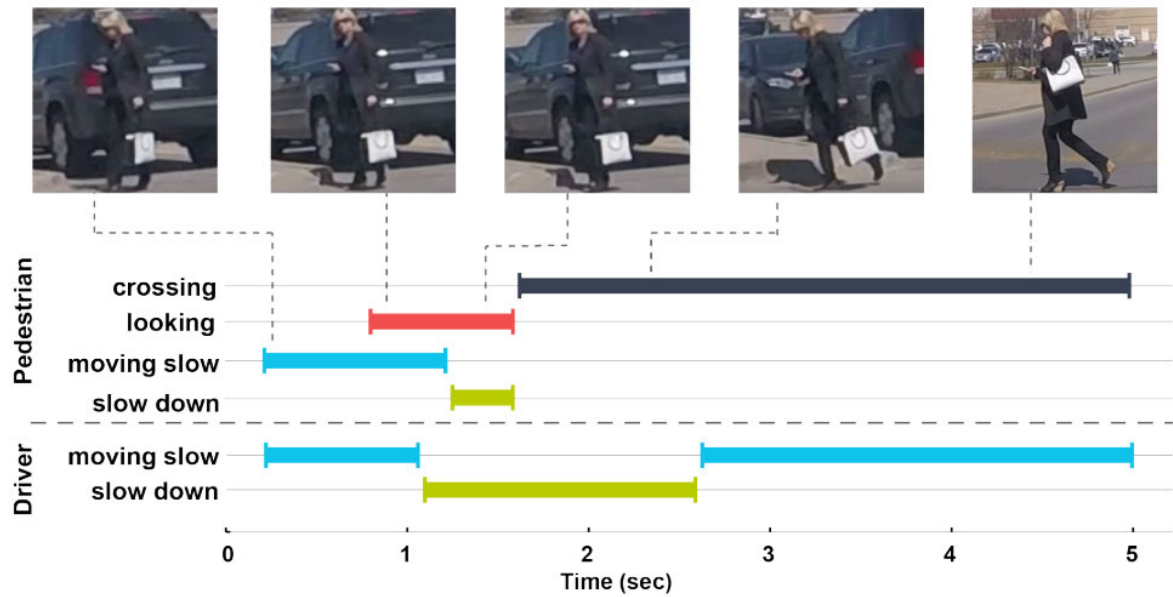


Fig. 2.26 Labeled pedestrian and driver behaviors in the vehicle-pedestrian interaction [127].

with an approaching vehicle. Any gap that is smaller than the critical gap supposed by the pedestrian will not be accepted for leading to a crossing behavior [128]. In the field study of G. Yannis *et al.* [129] who investigated the pedestrian gap acceptance in a mid-block crosswalk in the urban area, pedestrians' decisions and traffic conditions were video recorded. The results indicate that the gap acceptance was better explained by the distance from the vehicle to the pedestrian. Besides, based on their regression models, it is found that the pedestrian crossing decisions was affected by the distance from the vehicle to the pedestrian and the pedestrian waiting time.

The similar findings of the gap acceptance were noticed in a simulation-based study conducted by J. A. Oxley *et al.* [130]. In their experiments, the pedestrians with respect to different age groups were tasked with reporting their crossing decisions when facing an approaching vehicle at different distances to them. The results demonstrate that, for all the age groups, the selection of an acceptable gap primarily depended on the distance from the vehicle to the pedestrian. The pedestrians tended to make the positive crossing decision when the distance from the vehicle to them was large, disregarding the vehicle speed.

2.4.2 Explicit Communications

Automotive signal lights, such as blinking turn light and red stopping light, offer explicit communications which broadcast the vehicle next maneuver to pedestrians, two wheels, and other vehicles. Their positive effects on traffic interactions have been identified in terms of increased emotional arousal, higher fixation frequency, and longer fixation duration toward vehicles [131]. Besides, conventional usages of signal lights help drivers to convey additional messages, for instance, a vehicle use a flashing headlight to convey their yielding intention to pedestrians. However, it should be highlighted that the traffic context of using such signal light is important for interpreting its meaning. The intention conveyed by the same signal may vary

with respect to the traffic context [132]. For the same flashing headlight, it can also mean that a vehicle demands the front vehicle to leave the high-speed lane for making the overtaking on the highway or that a vehicle is giving a warning message to an inattentive road user in rural areas at night.

In vehicle-pedestrian interactions, auditory signals, like horns and engine sounds, also belong to explicit communications. Especially as regards the engine sound, it works to inform potential risks from near vehicles. However, this auditory signals will be eliminated with the introduction of electric vehicles which use silent electric motors. In the investigation of M. C. Pardo-Ferreira *et al.* [133] who studied risk situations produced by electric vehicles from the perspective of the pedestrian, it is pointed out that nearly half of the pedestrians considered that electric vehicles bring risks. This is because it is difficult to have awareness on these vehicles by hearing their sound. It is reported that the risk situations produced by electric vehicles usually occurred in low-speed urban areas.

2.4.3 Behavioral Communications

Particularly being relevant in vehicle-pedestrian communications, the behaviors, including gaze, facial expression, head movement, hand gesture, leg movement can be additionally taken into account for communicating the awareness and the intentions [54]-[56][127][134][135]. For instance, pedestrians search for the eye contact with drivers inside the vehicle in order to show their crossing intention. Drivers give hand gestures to pedestrians for letting them pass in priority. These behavioral communications are important for resolving ambiguities and conflicts between vehicles and pedestrians, which were mostly observed in low-speed and close-distance vehicle-pedestrian interactions.

M. Sucha *et al.* [54] investigated the communications and the decision-making strategies in vehicle-pedestrian interactions around marked crosswalks. It is identified that several factors, including speed, distance, traffic density, eye contact, and hand waving, can influence the pedestrian wait/go behavior and the vehicle yield/go behavior. Notably, searching for eye contact with the driver, as an important behavior, was carried out by most of the pedestrians to

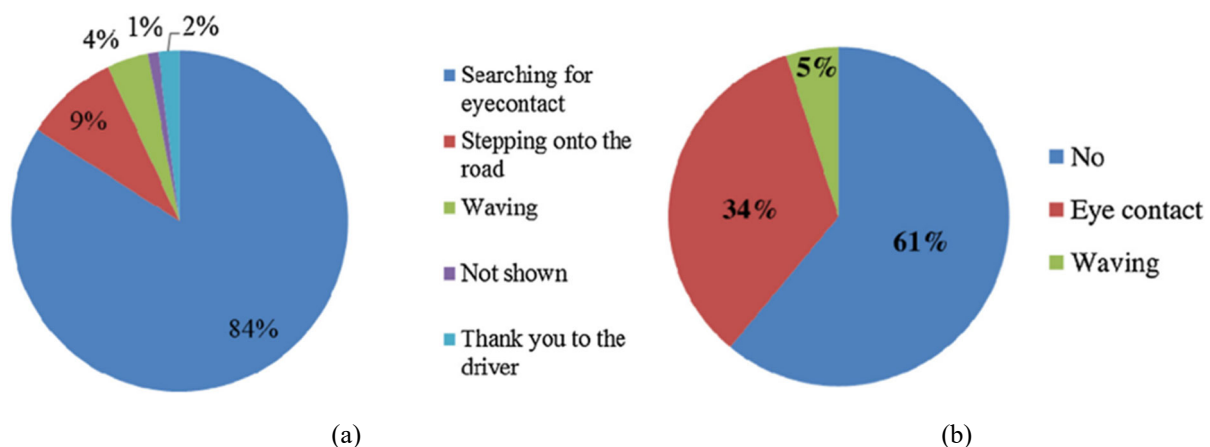


Fig. 2.27 How pedestrians show their crossing intention (a) and how drivers communicate with pedestrians (b) [54].

show their crossing intention (see Fig. 2.27). Moreover, the most common behavior which pedestrians found to be a sign which represents that drivers will give them the priority to cross the road was the vehicle slowing-down behavior or the complete vehicle standstill.

N. Gueguen *et al.* [56] studied particularly the gaze behavior and the compliance in the interactions between pedestrians who intend to cross the road and approaching vehicles with drivers inside. By the field experiments around crosswalks, it is found that if pedestrians looked drivers in their eyes for a few seconds, more drivers would stop to let pedestrians cross firstly. It is concluded that the eye contact seems to be an important nonverbal signal in the relationship between someone on the side of the road and drivers inside vehicles.

Not being limited within the eye, N. Gueguen *et al.* [55] studied the effect of a typical facial expression “smile” on drivers’ decisions. The tests asked the pedestrians to smile or not smile towards the drivers inside the oncoming vehicles around several crosswalks. It was found that the smile increased the number of drivers who stop the vehicle for pedestrians. The same effect was observed when the pedestrians tried to cross outside the crosswalk. These results suggest a smile as an appreciation signal towards drivers leads to the careful vehicle driving.

E. Vinkhuyzen and M. Cefkin [134] would like to know how pedestrians communicate with vehicles in the interactions where there are apparent conflicts about passing orders. Their video-based observations noticed that the pedestrians would not blithely step into the crosswalk in front of an oncoming vehicle. They would take a clear account of the vehicle behaviors before stepping in. Besides, it is found that the employment of hand waving by both pedestrians and drivers inside vehicles consisted of a common practice to negotiate who should go firstly.

A. Rasouli *et al.* [127] provided a novel video dataset for studying road users’ behaviors in road-crossing cases. By reviewing the video samples, it is identified that in more than 90% of the road-crossing cases, pedestrians gazed at approaching vehicles prior to crossing unsignalized crosswalks. Moreover, the other behavioral communications, involving nodding and hand gestures were observed in 15% of the cases. These behavioral communications often worked as the pedestrian’s response to the driver’s actions in order to express the gratitude, the acknowledgment, and the concession.

H. Persson [135] found that the likelihood for drivers to make a yielding decision increased if the information about pedestrian intention was received increasingly by the way of multiple behavioral communications. In the investigation, almost none of the drivers gave the right of way to the pedestrians around the crosswalk when the pedestrians just stopped at the curb. However, 31% of the drivers slowed down or stopped the vehicle before the pedestrians when the pedestrians looked towards the drivers and put their feet onto the road lane.

Among the research works on the behavioral communications, it should be highlighted that the pedestrian gaze behavior plays an important role in searching for information about the vehicle or the driver [127]. In the research works on the implicit communications, it is noticed that pedestrians gazed at the vehicle and perceived its speed for judging the vehicle intention [100]. The above evidence emphasizes the importance of pedestrian gaze behavior in seeking useful information to make the road-crossing decision. As regards the pedestrian gaze, the deeper studies have been done for exploring where pedestrians gaze at exactly in the interaction with vehicles. D. Dey *et al.* [136] conducted an eye-tracking study in a naturalist road-crossing scenario where a vehicle approaches, slows down, and gives the right of way to a pedestrian

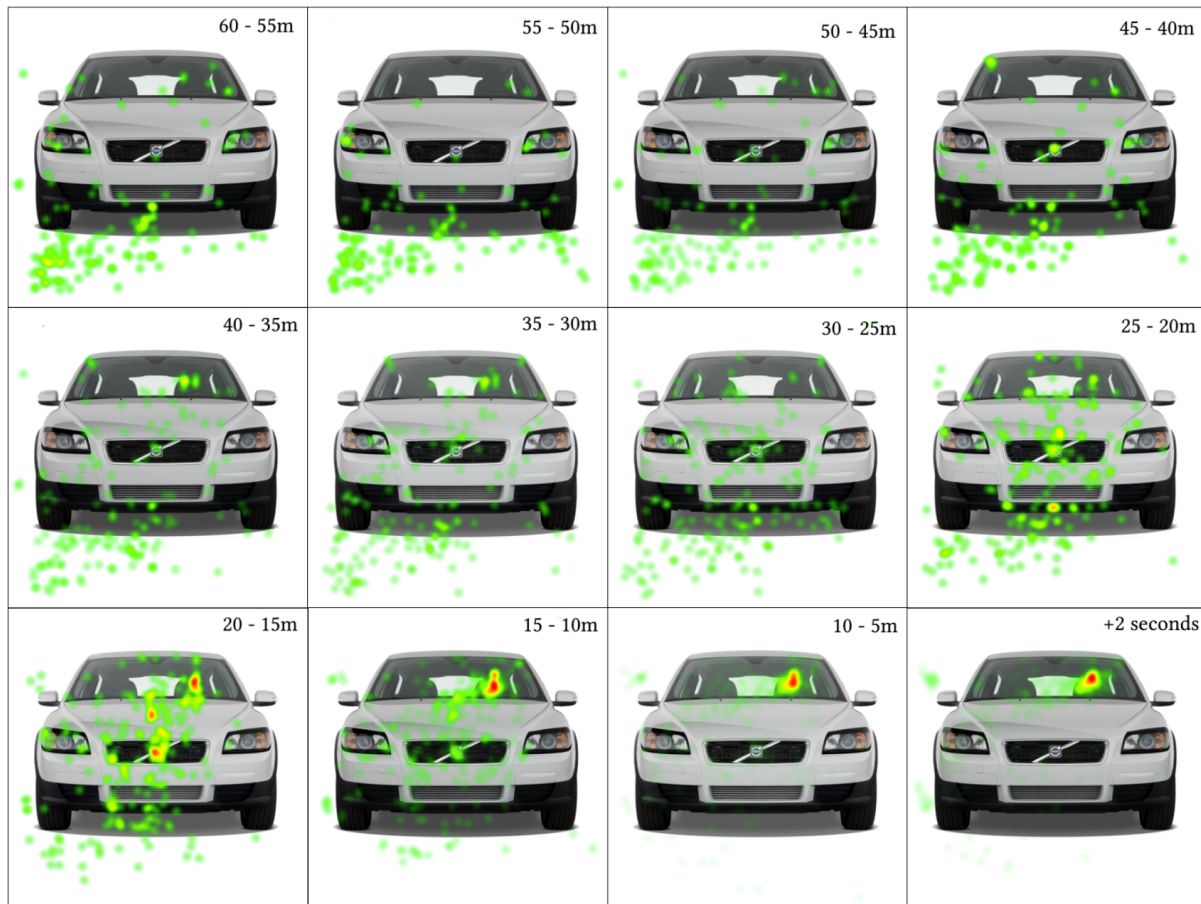


Fig. 2.28 Fixation frequency of pedestrian gaze towards the different areas around and on the vehicle as a function of the distance from the vehicle to the pedestrian in a pedestrian road-crossing scenario [136].

standing at the curb. The participants who play the role of the pedestrian were tasked with wearing the mobile eye tracker and looking towards the approaching vehicle. The data of fixation frequency show a clear pattern of pedestrian gaze as a function of the distance from the vehicle to the pedestrian (see Fig. 2.28). The fixation of pedestrian gaze tended to shift from the environments to the road surface ahead of the vehicle when the approaching vehicle was far away from the pedestrian. When the vehicle came closer, the fixation continued to slide from the vehicle bumper, grille, hood, to windshield. Notably, the pedestrian gaze finally fixated on the vehicle windshield in the vehicle-pedestrian interaction. This can be regarded as an indication that the pedestrian sought confirmatory information from the driver.

With the same method of eye-tracking, Y. B. Eisma *et al.* [137] evaluated their eHMIs for AV2P communications. Their eHMIs show two extended signals in five different places, including the roof, the windscreen, the grille, the area above the wheel, and the road surface. One extended signal is a pedestrian crossing sign associated with a text of “Waiting” for expressing the vehicle yielding intention. One other extended signal is a text of “Driving” associated with a text of the real-time vehicle speed for expressing the non-yielding intention. In their monitor-based experiments, the participants who wore the eye tracker were asked to view the animations of an approaching AV equipped with the eHMIs from the perspective of a pedestrian. Alongside, the participants had to press the spacebar when they felt safe to cross



Fig. 2.29 Gaze fixation (yellow point) towards the different areas around and on the vehicle in a pedestrian road-crossing scenario [137].

before the AV. The data of gaze fixation revealed that the road projection led to the dispersed eye movements, as the participants scanned back and forth between the signal projected on the road surface and the vehicle body (see Fig. 2.29). This suggested that road projection is visually effortful for pedestrians, as it causes them to divide their attention between the projection and the vehicle itself in the vehicle-pedestrian interaction. In terms of safety feeling, the data of spacebar-pressing show that the roof, the windscreen, and the grill draw the best performance. The road surface and the area above the wheels were scored poorly.

2.4.4 Summary: More Observations on vehicle-pedestrian interactions with particular attention to the Communication

The implicit, explicit, and behavioral communications are essential elements that influence the vehicle and pedestrian behaviors in their interactions. As demonstrated in the existing research works (see Fig. 2.30), implicit communications about the vehicle speed, the pedestrian speed and the distance from the vehicle to the pedestrian act as the important references for pedestrians to make the road-crossing decision. The explicit communications by the vehicle signal lights draw effectively pedestrians' attention and indicate vehicle next maneuvers. The behavioral communications enable the exchange of vehicles' and pedestrians' intentions for conducting to safe behaviors. Among them, it is notable that the vehicle speed variation works as an indicator to represent the vehicle intention [54][100][104]. The pedestrian gaze behavior towards the vehicle or the driver was generally employed for seeking information about vehicle speed or feedback from the driver [56][100][127]. As regards the suggested AV2P communication functions which apply the extended signals, they actually work as an explicit

source of information used to express the AV status and intentions, which are complementary to the existing explicit communications. Ideally, the AV2P communication functions can be regarded as the new and more powerful communications substituting the behavioral communications which will disappear due to the absence of drivers in AVs. Nonetheless, we noticed that most of the current concepts of AV2P communication functions were developed by dealing with pedestrians as immobilized objects in scripted interaction scenarios, instead of human beings who can take various behaviors [64][88]. Since pedestrians still highly rely on the basic communications through implicit, explicit, and behavioral channels to interact with vehicles, it would be preferable to take account of them in the development of AV2P communication functions. To do so, close observations on day-to-day vehicle-pedestrian interactions is needed with the purpose of looking for useful cues from the basic communications that vehicles and pedestrians rely on. Regarding the essential question about when to activate and where to place extended signals for developing AV2P communication functions, interesting ideas based on the basic communications were suggested in the existing research works. According to the fixation of pedestrian gaze, D. Dey *et al.* [136] and Y. B. Eisma *et al.* [137] discussed a group of places on or around the vehicle for employing extended signals, including bumper, radiator grille, windshield, roof, and road surface. Besides, for the activation timing of extended signals, the helpful cues can refer to D. Dey *et al.* [84] suggesting that the alignment between the new explicit communications and the actual implicit communications would facilitate the most effective communication of AV yielding intention. As the same, these suggestions need to be further confirmed by more observations on vehicle-pedestrian interactions with particular attention to the communication mechanism.

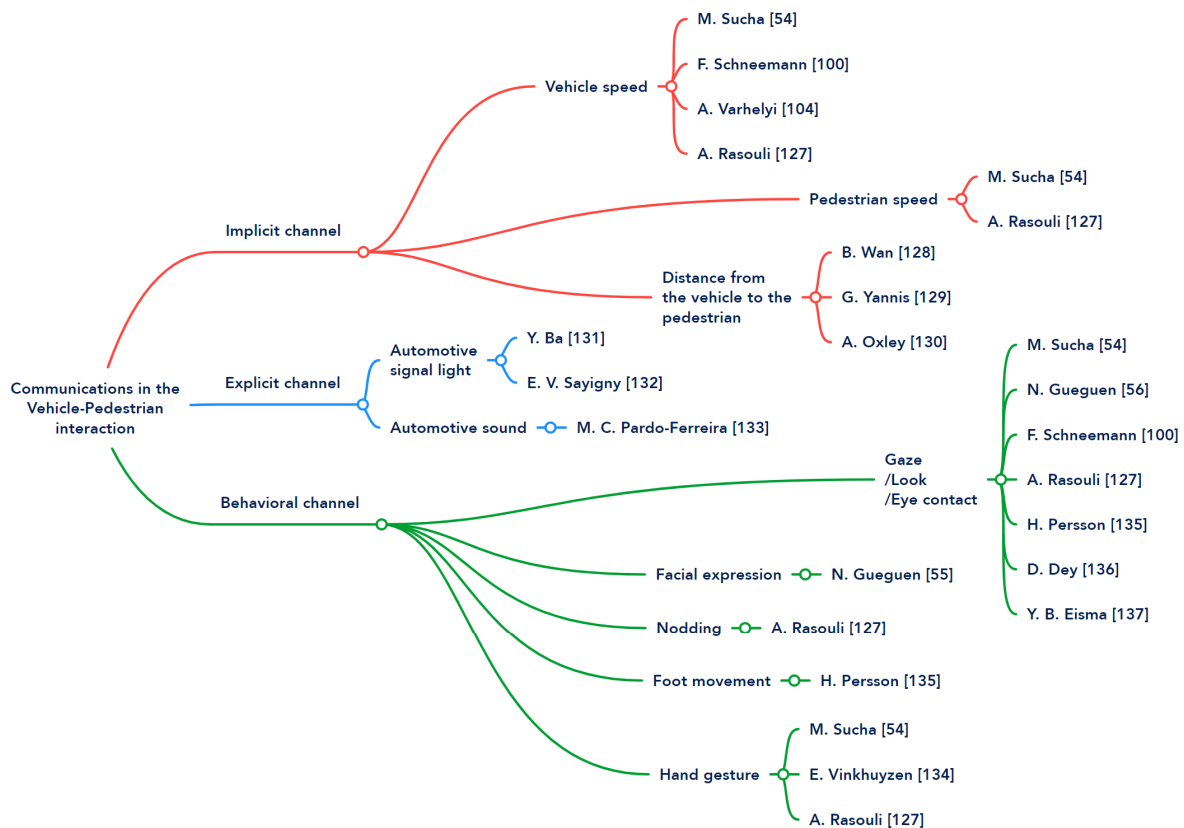


Fig. 2.30 Summary of research works which study the implicit, explicit, and behavioral communications in the vehicle-pedestrian interaction.

Chapter 3. Evaluating the Understandability of Light Patterns and Pictograms for AV2P Communication Functions

3.1 Context and Purpose

In order to facilitate safe and efficient AV-pedestrian interactions, AV2P communication functions through extended signals are of particular interest to express AV intentions. Recently, a large number of research works have investigated the effects of AV2P communication functions and their added values have been found in terms of promoting the recognition of vehicle intentions or improving the perceived safety towards vehicles [62][79][80][124]. It is notable that most of these research works have focused on whether the studied extended signals can bring positive effects on AV-pedestrian interactions. However, regarding the further question about what are the appropriate signal designs for the effective AV2P communication functions, there has been no consensus yet [116]. In the existing research works, the pedestrian crossing decision time and initiation time have been the usual indicators to evaluate the signal designs in the aspect of pedestrian behaviors. It is observed that compared to the signal designs composed of the well-known features, the abstract ones often performed badly for accelerating the pedestrian crossing decision-making and could even lead to the crossing decision error [106][120]. This suggests that the understandability of signals is a key factor that determines the decision of pedestrian behaviors through AV2P communication functions, whereas it has been less studied. According to A. M. Madni and M. Sievers [138], the overall goal with usability and systems integration is to assure interfaces can be adapted in a well-understood manner and with modest effort. In our case, for ensuring the effectiveness of AV2P communication functions, the used signals must be understandable. Therefore, it would be necessary to include particular studies on investigating as what exactly pedestrians understand extended signals in different forms. This is the main purpose of this chapter and it is expected the study on the understandability can provide helpful evidence for the selection of appropriate signal designs used for AV2P communication functions.

3.2 Scope of the Present Study

Nevertheless, this study on the understandability do not include all of the most discussed signal forms, e.g. texts, light patterns, pictograms, and anthropomorphism. Facing thousands of languages worldwide, the usage of texts would be restricted by the requirement of global standardization. As regards signals in the form of anthropomorphism, it is found that road users' current mental recognition can hardly adapt to them [121]. Hence, we chose to put eyes on light patterns and pictograms, which are suitable for achieving a universal adoption. With the purpose of evaluating the understandability of light patterns and pictograms, we need to design a series of signals in the forms of them, then study and compare their performance. In this study, we intentionally aimed at the vehicle-pedestrian encounter scenario around the crosswalk where

the designed signals are used to communicate the vehicle yielding intention, as it is a typical AV-pedestrian interaction case in future road systems and the clarity of right of way is important for traffic safety and efficiency. As regards the technologies used to show light patterns and pictograms, the turn indicator and the additional display device mounted on the vehicle were selected respectively. We did not select the road projection by considering that the perception of projected signals in real life may be constrained by the conditions of road surface and ambient light. Also, the existing research work reveals that the road projection can cause pedestrians to divide their attention between the projected signals and the vehicle itself. This is effortful for pedestrians in their interactions with vehicles [137].

For the specific signal designs, it is identified from the existing research works that, unlike light patterns, pictograms can be designed with respect to two content types: those convey an advice message from an egocentric perspective taken by the pedestrian such as crossing or walking, and those state information about the vehicle from an allocentric perspective, such as stopping or braking [111][123]. Both of them can be used to communicate the vehicle yielding intention. So far, the difference of understandability between these two types of pictograms in AV2P communications has not been sufficiently clear and would require more studies.

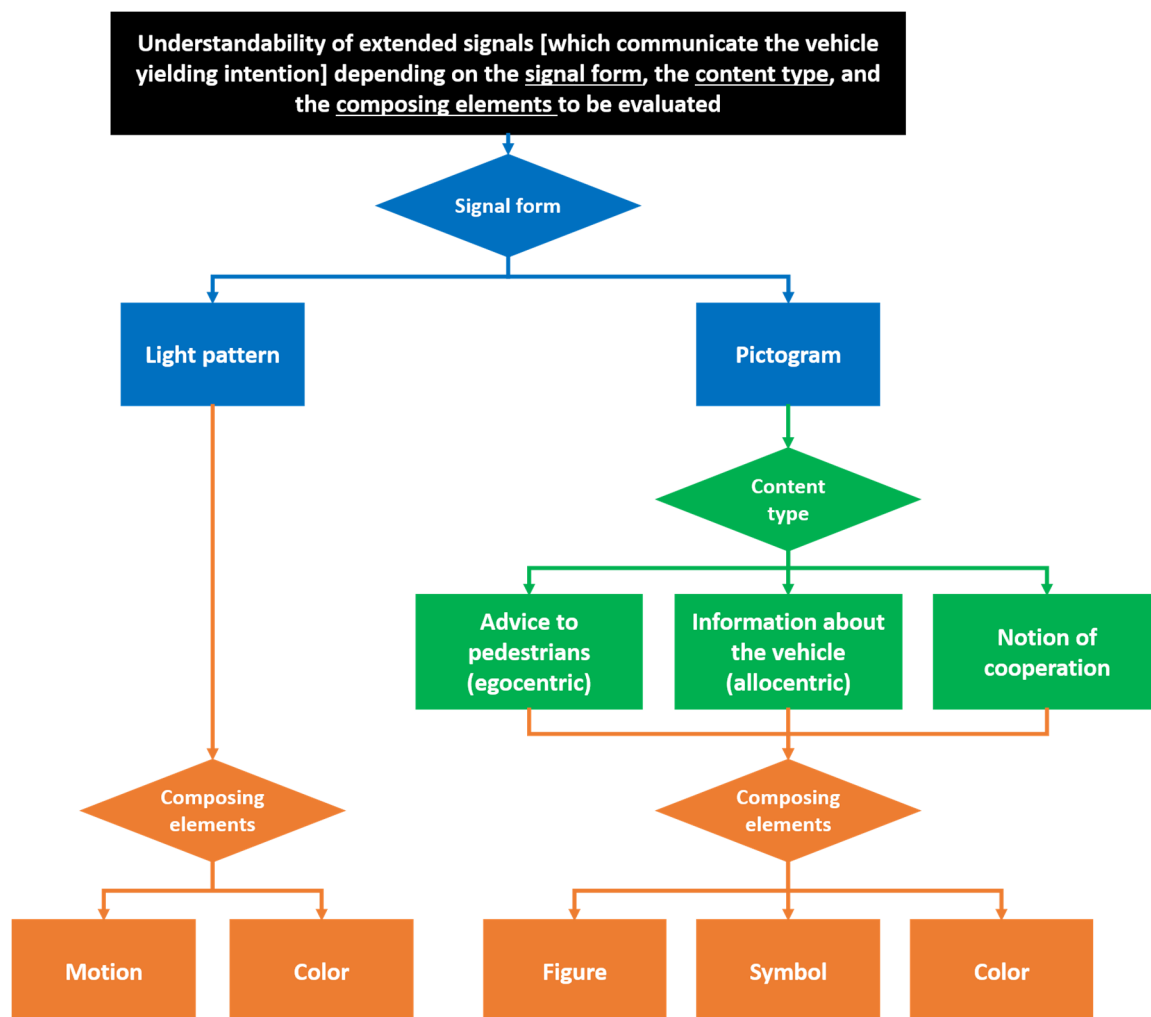


Fig. 3.1 Scope of the present study: Understandability of extended signals depending on the signal form, the content type, and the composing elements.

Moreover, light patterns with different motions and colors, and pictograms with different figures, symbols, and colors can own different understandability. They were observed to have different influences on the decision of pedestrian behaviors. It would be useful to study the understandability depending on these composing elements for revealing their effects on whether they contribute to a correct understanding or cause confusion. It is expected that the related results can provide some useful design basis for extended signals used in AV2P communication functions.

Therefore, the light patterns to be evaluated in this study were designed by differing in motion and color. The pictograms which convey an advice message or state information about the vehicle were designed by differing in figure, symbol, and color. Moreover, we added a third type of pictogram which combines an advice message and information about the vehicle to convey a notion of cooperation, by supposing that it can be another possibility for communicating the vehicle yielding intention. Accordingly, these signal designs allow us to study in a controlled manner the understandability depending on the signal form (light pattern, pictogram), the content type (egocentric advice, allocentric vehicle information, notion of cooperation for the pictogram), and the composing elements (motion and color for the light pattern, figure, symbol and color for the pictogram) (see Fig. 3.1).

For guidance, this chapter introduces in the following the details of our signal designs. Then, the method used to evaluate the understandability by monitor-based tests are demonstrated. After that, we illustrate the obtained results, upon which the analysis on the performance of light patterns and pictograms are carried out. In the end, we draw the limitations of this study, conduct the conclusion on the understandability of light patterns and pictograms, and give the recommendations to the design of extended signals for AV2P communication functions.

3.3 Signal Design

The task of signal designs was realized in collaboration with three junior designers from STRATE school of design in France. We spent one week discussing and designing together a series of signals in the forms of light patterns and pictograms which express the vehicle yielding intention to pedestrians. During the design process, a common methodology was applied, consisting of clarifying the requirement for signal designs, learning knowledge and cues for reaching the requirement, summarizing the useful points, constituting the design principle, and finally realizing the signal designs. About the requirement for signal designs, it is clear in this study, which is to communicate the vehicle yielding intention to pedestrians in a well-understood manner in the vehicle-pedestrian encounter scenario around the crosswalk.

3.3.1 Basic Knowledge and Cues for the Signal Design

To learn basic knowledge of how to make the signals understandable, we attempted to review the design guidelines for light patterns and pictograms in the existing research works. As a result, several useful ways to design understandable pictograms were found, but we could hardly find the information about how to design light patterns. This is probably because light

patterns composed of motions and colors are naturally meaningless. They own much little room for a causal design. It is the designer who decides and gives meanings to light patterns. Still, one exceptional point about the color should be highlighted. Presently, people are already used to the meanings of some colored light in traffic. For example, the green traffic light generally means the permission to go and the red traffic light means that the action must stop. These conventional meanings of the colored lights may influence people's understanding new light patterns. Overall, agreeing with the junior designers, we argued that there is not much existing knowledge that can be based on for improving the understandability of light patterns.

For the design of pictograms, our learning started from clarifying their definition. A pictogram is a stylized drawing composed of figural, symbolic, and colored representations, which is used to convey messages. Pictograms are generally applied to replace written indications and instructions when they must be processed quickly such as road traffic signs [139]. There are a lot of recognized advantages of pictograms [140]. They have the potential to be recognized more accurately, more quickly, and from a longer distance as compared to texts [141]. They can overcome the language barrier when users speak different languages or have limited linguistic ability. Furthermore, as regards how to make pictograms be more understandable, R. S. Easterby and H. Zwaga [142] underline the importance of familiarity and report that familiarity with a sign improved its comprehension. Similarly, M. Pelegrina and J. Gallifa [143], and F. Beltran and Y. Auque [144] suggest using familiar and typical images in pictograms. They also mentioned that users' understanding of pictograms does not depend on the number of features but mainly on familiarity. Besides, for representing an object or a notion, the figure or symbol used in the pictogram can be designed with respect to the different semantic distances [145]. For example, a pedestrian can be represented by a figure of a walking people in a semantically close way or it can be represented by a figure of a pair of feet in a semantically distant way. According to S. J. McDougall *et al.* [146], the semantic distance rather than the concreteness should be the main determinant of the comprehensibility of pictograms. Furthermore, C. Tijus *et al.* [147] investigated the influence of usage contexts on understanding a pictogram. They found that the context in which a pictogram is expected to be perceived can lead to a more accurate interpretation. Besides, when a pictogram is composed of more than one element, it should be known that the whole of a pictogram is more than the sum of its composing elements in terms of understanding [148][149]. This insight can be further linked to A. B. Magurno *et al.* [150], who recommend to carry out a sequential design approach for pictograms. This means to start the design of a pictogram with a basic component, then review and add more components step by step until an optimal understandability level is obtained. Nonetheless, it needs to be known that adding components makes the pictogram become more complex [151]. Besides, D. Shinar *et al.* [152] identified several underlying factors that affect the understandability level of signs, including spatial, conceptual, and physical compatibility, familiarity, and standardization. They argue that well understandable signs should be consistent with several of these cognitive principles.

In addition to the above knowledge obtained from the research works, we also observed and registered a large number of signals applied in daily life, especially in the transportation involving automobile, railway, and aviation. This work is for discovering useful cues for designing light patterns and pictograms which express the vehicle yielding intention. As regards light patterns with different motions and colors, we observed in the automotive signalization that there appears recently a trend of using dynamic light motions. More and more vehicles are equipped with the sequential turn indicators which can show a rapid motion sweeping from the

inside to the outside (see Fig. 3.2a). Moreover, as being well-known, the usage of headlamps by successively switching on and off the high beam are frequent in some ambiguous traffic scenarios. One important intention of this light motion is to tell pedestrians that the vehicle will yield to them. Another interesting light pattern that can be seen from time to time is the blue light with a rotating motion used by police and ambulance cars. Furthermore, in the aspects of railway and aviation, it is observed that the crossing grade light before a railway passage shows a distinct light pattern. Based on a pair of horizontally separated lamps, two red signal lights blink in turn for demanding coming vehicles to stop and yield to the train (see Fig. 3.2b). Interestingly, this light pattern can also be found in the alternating landing light system introduced several years ago on airplanes. This system activates alternatively the left and right landing lights to achieve an attention-getting purpose and indicate that the airplane is about to land (see Fig. 3.2c). Besides, we continued to explore the railway signalization system and found that the groups of multiple signal lights in different colors are used to guide train drivers for speed adjustment. In other aspects, it is found that a pulsing light with an increase and decrease luminous intensity are often used in the status indicator of electronic devices, such as external camera or robot vacuum cleaner. This light motion is for saying that the device has stopped working or it is in a standby mode (see Fig. 3.2d).



Fig. 3.2 Sequential turn indicator (a), crossing grade light (b), alternating landing light system (c), status indicator of an external camera (d), road sign: give way to oncoming vehicles (e), dotted line on the road: yielding to other traffics (f), road sign: no overtaking for trucks (g), road sign: drive on left (h), road sign: pedestrian crossing (i), road sign: downhill (j).

As regards pictograms, our observation is mainly on road signs and markings relevant to the pedestrian, the yielding indication, and the priority of way. The first notable one consists of the road sign, composed of a classic pedestrian figure and a crosswalk field figure. This road sign is used to notify that there is a crosswalk for pedestrians ahead. Besides, the road sign, composed of two arrow symbols in black and red, deserves to be highlighted (see Fig. 3.2e). This road sign is for indicating that the vehicle should give way to oncoming vehicles. Actually, this road sign uses a pair of arrow symbols in the opposite colors to indicate the expected mutual actions of the traffic actors on the two sides. With it, the priority of way and the indication of yielding can be understood in a very simple way. The other one with the similar design is the road sign, composed of two vehicle figures in black and red (see Fig. 3.2g). It is used to inform that the vehicle has no right to overtake. Moreover, the road marking composed of dotted lines is noteworthy. It can be met frequently around crosswalks, intersections, and roundabouts, which is for indicating that the vehicle should yield to other traffics (see Fig. 3.2f). Accordingly, the design of the above road signs inspired us to put eyes on their composition. It is observed that a road sign is mainly composed of (a) figure(s), (a) symbol(s), along with (a) color(s). Being different from the signs used in other places, the road signs still need to be completed with a colored background and a colored border. For these composing elements, the figure generally takes the role in illustrating the concerned traffic actor and the concerned field of traffic scenario (see Fig. 3.2g, h, i, and k). The symbol is generally used to represent the expected action of traffic actor (see Fig. 3.2e and h). The color added to the figure and the symbol can supplement an additional meaning such as permission, prohibition, going, and stopping (see Fig. 3.2e and g). Particularly, the different colored backgrounds and borders used in the road signs own the standard meanings including prohibition, mandate, warning, and safe condition (see Fig. 3.2g, i, and k).

3.3.2 Design Principle

The existing research works and the observation on the signals in daily life provide several useful knowledge and cues for designing the understandable signals. We selected some of them which is usable for this study to constitute the design principle. For the pictogram, we decided to respect the sequential design approach by selectively adding and combining the composing elements step by step [150]. The composing figures, symbols, and colors that we proposed to represent the traffic actors, the expected actions, and the fields of traffic scenarios were borrowed directly from those already used in the current frame of road signs and markings. This is because they are the familiar features for the public who can take advantage of their traffic experience to understand them [143][144][153]. We chose to not take account of the colored background and border, as they are the particular features with standard meanings. Also, adding them will unnecessarily make the pictograms become complex [151]. Besides, since we borrowed the figures, symbols, and colors used in the current frame of road signs and markings, it can be supposed that the composed pictograms are basically consistent with the ergonomic principles in terms of conceptual and physical compatibility, familiarity, and standardization [152]. Nevertheless, in the case that the arrangement of composing elements in a pictogram is needed, we took account of the spatial capability for that the composing elements are relative to the position and direction in real usage conditions [152].

Table 3.1 Signal designs in the forms of light patterns differing in motion and color, and in the forms of advice, information, and cooperation pictograms differing in existence or absence of actor figure, action symbol, field figure, and color

Light pattern	N°	01	02	03	04	05	06	07	08	09
	Motion	Conventional blink 1. 2.			Double fast blink 1. 2. 3.			Alternating blink 1. 2.		
	Color									
	N°	10	11	12	13	14	15			
	Motion	Round-trip sweeping 1. 2. 3.			Breath-effect 1. 2. 3.					
	Color									
Advice pictogram	N°	16	17	18	19	20				
	Design									
	N°	21	22	23	24	25				
	Design									
	N°	26	27	28						
	Design									
Information pictogram	N°	29	30	31	32	33				
	Design									
	N°	34	35	36	37	38				
	Design									
	N°	39	40	41						
	Design									
Cooperation pictogram	N°	42	43	44	45	46				
	Design									
	N°	47	48	49						
	Design									

For the light pattern, its composing elements are relatively simple which consist of the motion and the color. Thereby, we decided to combine different motions and colors for designing the light patterns. However, as mentioned above, the motions and the colors are naturally meaningless, so that we cannot make too many efforts to improve their understandability. Yet, inspired by the importance of familiarity [142], we intentionally proposed the combinations of motions and colors by adapting to the existing and familiar light patterns that we can meet in daily life, especially those containing the meaning of yielding and stopping.

3.3.3 Design of Light Patterns

By following the defined design principle, the design of the light patterns which communicate the vehicle yielding intention was realized by combining five motions and three colored lights (see the first row of Table 3.1). To distinguish the motions, they are respectively labeled as “conventional blink”, “double fast blink”, “alternating blink”, “round-trip sweeping” and “breath-effect”. The conventional blink is an imitation of the basic motion of today’s automotive hazard light. The double fast blink consists of two fast and successive blinks, which is inspired by the successive switching on and off of the high beam for calling the attention of or yielding to other road users. The alternating blink is based on a pair of light units blinking in turn. This light motion imitates the grade crossing light used to signal the yielding of vehicle to the train. The round-trip sweeping is a sequential light motion sweeping between the inside and outside of a series of light units, which is inspired by the trend of sequential turn indicators. The breath-effect is a pulsing light with an increase and decrease of luminous intensity, resulting in a “breath” animation. This motion is inspired by the status indicator of electronic devices, indicating a standby mode. The three colored lights are labeled as “white”, “cyan” and “bi-color”. Currently, white lights are used by automotive day running lights in a static mode. We suggested that the combinations of the white color and the motions can convey new messages. This can also be applied to other colors, like cyan which is recommended as a new dedicated light color for AVs [96]. We also proposed a bi-color configuration where the white light with the motions and the static cyan light are grouped. This configuration is inspired by the railway multi-color signalization system. Finally, the combinations of these motions and colors yielded fifteen different light patterns. Compared to the existing research works, it is noticed that the conventional blink, the round-trip sweeping, and the breath-effect are nearly the same as the signals proposed by T. Lagstrom and V. M. Lundgren [27], S. Faas and M. Baumann [117], and A. C. Hensch *et al.* [83].

3.3.4 Design of Pictograms

As described previously, for communicating the vehicle yielding intention, the pictograms can be designed with respect to two content types: those convey advice of crossing from an egocentric perspective taken by the pedestrian and those state information about vehicle stopping from an allocentric perspective [111][123]. To distinguish them, these two types of pictograms were labeled respectively as “advice pictogram” and “information pictogram”. Moreover, by combining both of the above, we proposed a third type of pictogram which

conveys a notion of cooperation. Inspired by the road sign composed of two arrow symbols or two vehicle figures with the opposite colors (see Fig. 3.2e and g), this type of pictogram represents the expected mutual actions between the crossing pedestrian and the stopping vehicle. It is expected that this type of pictogram can establish the cooperation between the vehicle and the pedestrian by clarifying the right of way. To distinguish it, it was labeled as “cooperation pictogram”.

With the purpose of representing the traffic actor, the expected action, and the field of traffic scenario with respect to these three types of pictograms, the related figures, symbols, and colors were proposed by borrowing those already used in the current frame of road signs and marking.

The advice pictograms conveying advice that the pedestrian can cross (see the second row of Table 3.1) can use a classic pedestrian figure to directly represent the concerned traffic actor. A figure of a pair of feet can also represent the concerned actor in a semantically distant way [145]. For representing the crossing action, we chose an arrow symbol. For representing the field of vehicle-pedestrian encounter scenario around the crosswalk, a simple crosswalk figure was selected. Additionally, we proposed that the green color can be added to the actor figure or the action symbol to express the permission of crossing.

The information pictograms conveying information that the vehicle is stopping (see the third row of Table 3.1) can rely on a classic vehicle figure, or a figure of a foot with a pedal in a semantically distant way to represent the concerned traffic actor. A dotted line symbol was chosen to represent the action of stopping, which is inspired by the road marking indicating the stopping to give the way. For representing the field of encounter scenario around the crosswalk, a simple crosswalk figure was selected. Additionally, we suggested that the red color can be added to the actor figure or the action symbol to express the meaning of stopping.

The cooperation pictograms conveying that the pedestrian has the right of way in priority to the vehicle (see the fourth row of Table 3.1) can rely on the same actor figures, action symbols, and field figure as those proposed for the advice and information pictograms. The opposite colors, green against red, were added to the actor figures or the action symbols as a default composing element for meaning that the priority belongs to the pedestrian, rather than the vehicle.

Eventually, thirteen advice pictograms, thirteen information pictograms, and eight cooperation pictograms were proposed by selectively adding and combining the actor figure, the action symbol, the field figure, and the color. Notably, some of the advice pictograms that we proposed show the similarity with those studied by I. Othersen *et al.* [106] and S. Stadler *et al.* [120].

3.4 Method

3.4.1 Monitor-Based Tests on the Signal Designs

In order to evaluate extended signals used for AV2P communication functions, the usual experimental setup is simulating the studied traffic scenario and showing the signals to be tested in a real-world environment [62][80], a monitor-based environment [108][123], or a VR-based environment [109][120][124]. Ideally, it would be better that extended signals can be demonstrated and evaluated with the help of a functional AV equipped with AV2P

communication functions in the real world. However, this setup has never been possible so far. This is owing to the considerations regarding feasibility and safety. An AV requires a vast amount of efforts and resources to develop, and the potential safety issues do not allow to apply them in regular traffic yet. Hence, few research works, which have evaluated the extended signals in the real world, employed the Wizard-of-Oz method [27]. The Wizard-of-Oz method consists of pretending the typical feature of an AV by having an operator hidden inside a special seat suit or using a hidden steering wheel. Only after the tests, subjects were informed of the relevant test setup. One important advantage of this setup is that it allows a naturalistic observation on subjects' behaviors outside the laboratory. Nevertheless, the majority of research works were carried out in the monitor-based or VR-based environment. As regards the setup in these two environments, the demonstration of extended signals and traffic scenarios is generally realized in the form of the animated scene. When experiencing the animated scene, subjects are asked to accomplish some test tasks and related data are recorded. Importantly, this setup allows for a flexible numerical modification of the animated scene and guaranteeing the safety of subjects [107][108][123]. Besides, with the setup in the monitor-based environment, the tests can be widely spread through an online interface, by which subjects can participate in the tests with their computers in an autonomic manner [111]. However, this setup may lack realism to a certain extent. For the tests with the setup in the VR-based environment, subjects who wear the specific headset and move within a confined space can experience immersive animated scenes which simulate extended signals in traffic scenarios. This setup is able to supplement added realism. Furthermore, it allows for the measurement of some behavioral data, including crossing decision time and crossing time with the support of time counting instruments [109][120][124].

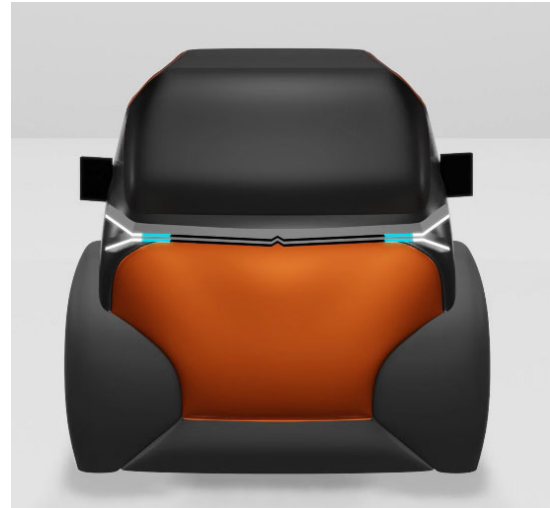
When a large number of signal designs with minor design variations need to be tested, an efficient method for the early-stage evaluation is desirable for narrowing the pool of signal designs by selecting the most promising ones [111]. Hence, considering the number of signal designs proposed in this study, monitor-based tests in an online interface which are flexible and can be widely spread are most preferable. VR-based tests were not selected, as the organization of hundreds of subjects in the laboratory to test a big number of signal designs was estimated to take a long time, and the high realism of the simulation is not an absolute condition for the purpose of evaluating the understandability. Exceptionally, the pandemic of Coronavirus starting from 2020 provoked huge impacts on a wide range of sectors. For respecting the health policy, using an online test interface to carry out monitor-based tests, rather than inviting subjects to be present in VR-based tests can reduce the unnecessary contact between people. Thereupon, we opted for the monitor-based tests in an online interface which demonstrate the signal designs to be tested in the AV2P communications through the animated scenes. Meanwhile, the subjects' understandings on the signal designs were recorded by completing compact surveys in the interface. This allowed for widely spreading and efficiently recording the subjects' understanding of the signals.

3.4.2 Test Stimuli

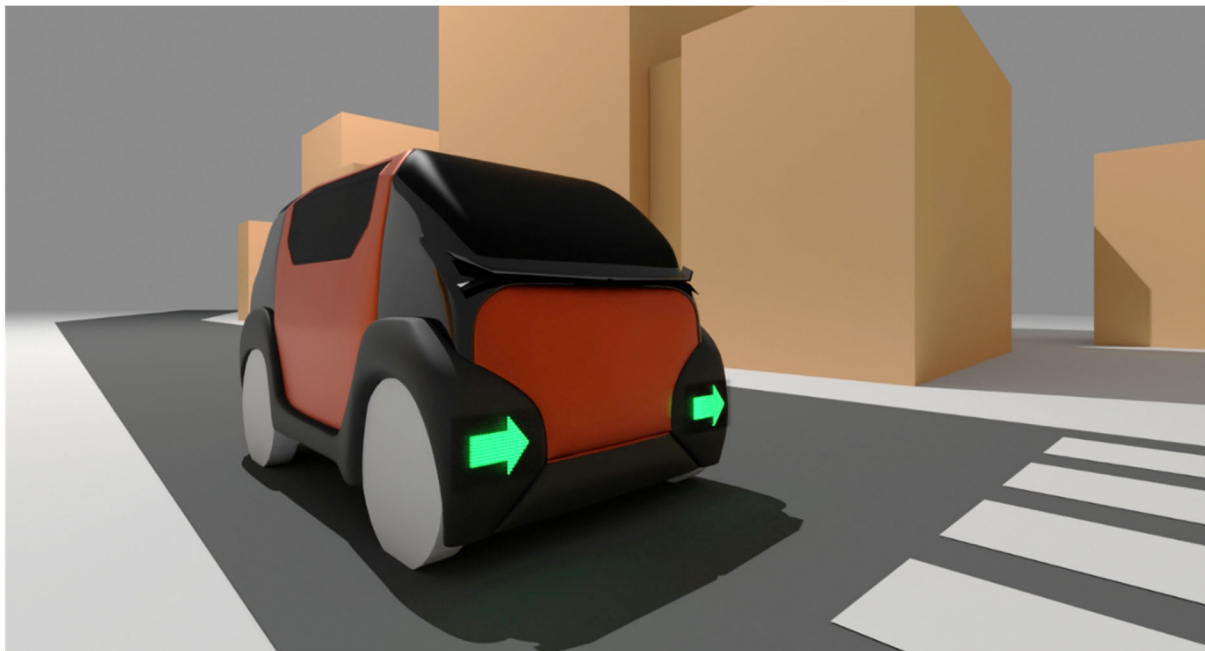
Stimuli in the form of the animated scene were created by the open-source software Blender, representing a 3D vehicle model to show the signal designs to be tested in different virtual



(a)



(b)



(c)

Fig. 3.3 Citroën Ami One Concept as the basis of the 3D vehicle model (a), Light pattern, combined of the conventional blink and the bi-color light, tested with the blank background (b), Advice pictogram, combined of the arrow symbol and the green color, tested with the vehicle-pedestrian encounter scenario (c).

contexts. The 3D vehicle model was produced on a basis of the Citroën Ami One Concept by respecting its appearance and architecture as real as possible (see Fig. 3.3a). The driver cabin of the 3D vehicle model was shaded by a non-transparent windshield for hiding the driver, which creates an illusion of an AV [120][123]. The proposed light patterns were integrated into the vehicle turn indicators (see Fig. 3.3b). The proposed pictograms were shown by two additional display devices installed on both sides of the vehicle bumper (see Fig. 3.3c). The vehicle bumper was defined as one area of interest to place extended signals, based on our study of vehicle-pedestrian interactions [154].

3.4.3 Test Contexts

The test stimuli demonstrate the signal designs to be tested with two virtual contexts: blank background, where the 3D vehicle model is placed steadily with a white background (see Fig. 3.3b), and the vehicle-pedestrian encounter scenario around the crosswalk, where the 3D vehicle model is placed with a background featuring a bi-directional road around a crosswalk (see Fig. 3.3c). The blank background aims at evaluating the inherent understandability of the signal designs in the condition where no external influence exists. The encounter scenario aims at evaluating the understandability of the signal designs under the influences of vehicle behaviors and surrounding environments. Regarding the encounter scenario, the approaching vehicle slows down, activates the signalization to express its yielding intention, and comes to a stop before the crosswalk. After a few seconds of waiting, the vehicle switches off the signalization and restarts to go forward. The stimuli of the encounter scenario are set from the point of view of a pedestrian who stands at the curb and intends to cross the road. The vehicle approaching speed is set as 30 km/h. The timings of vehicle slowing-down and activating the signalization are set respectively at the moments when the distance between the vehicle and the pedestrian are at 14 m and 12 m. This setting is based on our field observation study on the spatio-temporal relationship between vehicles and pedestrians in their interactions around urban crosswalks [154].

3.4.4 Test Interface

The online test interface on a website was programmed with the PHP code and was developed to present an interactive survey to test subjects. The mainframe of the test interface is a large PHP form divisionally presented in several pages, along with the style-fixed video player. Several JavaScript functions integrated into the test interface were developed to preset and advance the survey. The PHP form works on showing the established texts, collecting subjects' inputs in terms of written text, option, and scaled rating. It also works on submitting the inputs with a defined structure to the database server. The style-fixed video player works on demonstrating the test stimuli in the form of MP4 whose playback cannot be controlled by subjects. The preset function was developed to select and read the test stimuli stored in the database server, then associate it with the video player. The button function was developed to realize the page transition for advancing the survey.

People who have the website link (<https://onlinetest.embedded-lighting.com>) can visit freely our online test interface. The invitation to the test was shared to the public through scholar bulk emails, crowdfunding survey platforms, LinkedIn, Facebook, and Instagram with the help of our research team.

3.4.5 Test Procedure

Starting from the welcome phase, the test interface gave a brief introduction to visitors, which states that this test aims at evaluating new automotive signals and the participation in the test requires the acceptance of providing the demographic information about gender, nationality,

age, and driving experience (see Table 3.2). The visitors who gave the acceptance and the required information were considered as the test subjects.

Then going into the instruction phase, the subject was asked to read carefully the test instructions explaining that the task for the subject is to watch a video animation containing one signal, then select whether he or she understands the signal meaning, and respond to some questions. No other information about the signal was further provided in order to ensure that the subject had no prior knowledge of it.





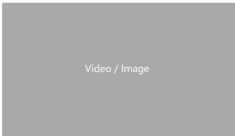


When the subject was ready, the test phase started by clicking a start button. During the test, a stimulus in the form of the animated scene was displayed by a video, containing one of the forty-nine signal designs randomly selected, with one of the two test contexts also randomly selected. The subject had to select “I understand” or “I don’t understand” the signal meaning through two specific buttons. When the option “I understand” was selected, the subject was required to give a written interpretation on the signal meaning. Then, the subject had to rate from 1 to 5 the certainty about his or her interpretation. Otherwise, when the option “I don’t understand” was selected, neither interpretation nor certainty degree was required, and the test went to the end directly.

For each subject, completing the test was only allowed once. This was determined by considering that successive tests in which the same subject experiences several signal designs with the same meaning may contain biases due to the learning effect. Provided that the subject has learnt after several tests that the signal designs always mean the vehicle yielding intention, this subject can thereby give the correct interpretation though he or she does not actually understand the signal design latterly tested.

3.4.6 Indicators to Evaluate the Understandability

In spite of the importance of understandability, the research works which have investigated this factor are not many. Among them, the scaled rating of clarity or comprehensibility is a subjective indicator used to evaluate the understandability. P. Bazilinskyy *et al.* [111] launched an online survey to investigate the clarity of diverse eHMI concepts through the scaled rating. The obtained results show some interesting opinions on eHMI concepts from the subjects. However, it should be pointed out that these opinions in terms of rating of clarity could hardly provide the useful insights on why some kinds of eHMIs lost their promised functions. In their results, the eHMIs using light patterns to communicate the AV intention were rated as relatively unclear. However, why they cannot clearly express the AV intention was not explained accordingly. Besides, the rate of interpretation correctness is also an indicator used to evaluate the understandability of extended signals. In the study of M. Hamn *et al.* (2018), each of the pictograms for communicating the vehicle intention was demonstrated on the automotive display devices and the subjects were tasked to associate it with the correct meaning. Upon the associations, the rate of interpretation correctness was calculated in order to evaluate the understandability. Literally corresponding to the definition of “understand” which is perceiving or interpreting the intended meaning of something in a particular way, it is reasonable to rely on this indicator to evaluate the understandability of extended signals. Nevertheless, the cognition process of “understand” is more than the interpretation correctness. As regards the

Table 3.2 Test procedure for evaluating the understandability of the signal designs: welcome, instruction, and test phases.

Welcome phase	
<div style="display: flex; justify-content: space-around; align-items: center;">     </div> <p style="text-align: center;">ONLINE TEST (Duration: 5 minutes)</p> <p>Evaluation of The New Form of Automotive Signalisation</p> <p>This test is conducted by ELS Chair, Hubert Curien Laboratory, with the support of PSA group and Automotive Lighting.</p> <p>The goal of this online test is to evaluate new forms of the automotive signalisation. Your feedback would be helpful for our research.</p> <p>Some of your information (gender, age, nationality and driving experience) is required. These information will be strictly protected and only be used for the research purpose.</p> <p>Please participate in this test only once.</p> <p style="text-align: right;"><input type="button" value="I accept to participate"/></p>	<p>Gender: <input type="text"/> Age: <input type="text"/> years old Country: <input type="text"/> Driver license: <input type="text"/></p> <p style="text-align: right;"><input type="button" value="Next"/></p>
Instruction phase	
<p>Test instructions</p> <ol style="list-style-type: none"> 1) The light signal to be tested will be shown in a video or image. You will have to press the button START to view it. 2) You will have to indicate whether you understand the meaning of the light signal. <ul style="list-style-type: none"> - If you understand what the car wants to communicate by the light signal, please press the button I UNDERSTAND immediately. - If you don't understand, please press the button I DON'T UNDERSTAND. 3) Then, you will have to answer some questions. <p>Notice: In the case where you can't view clearly the video or image, please adjust manually (Ctrl + mouse scroll) the resolution of your navigator.</p> <div style="display: flex; justify-content: space-around; align-items: center;"> <div style="text-align: center;">  <p>Video / Image</p> <p><small>Test preview</small></p> </div> <div style="text-align: center;"> <div style="border: 1px solid black; padding: 2px;">I UNDERSTAND</div> <div style="border: 1px solid black; padding: 2px;">I DON'T UNDERSTAND</div> </div> <div style="text-align: center;">  <p><small>Front view of the car in the test</small></p> </div> </div> <p style="text-align: right;"><input type="button" value="Start the test"/></p>	
Test phase	
<div style="display: flex; justify-content: space-between; align-items: center;">  <div style="text-align: right;"> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">I UNDERSTAND</div> <div style="border: 1px solid black; padding: 2px;">I DON'T UNDERSTAND</div> </div> </div>	
“I understand”	“I don’t understand”
<div style="display: flex;"> <div style="flex: 1; background-color: #d3d3d3; min-height: 100px;"></div> <div style="flex: 1; padding: 10px; border: 1px solid black; margin-left: 10px;"> <p>What the car wants to communicate by the light signal? <small>(please give your most detailed answer)</small></p> <div style="border: 1px solid black; height: 20px; width: 100%;"></div> <p>How confident are you about your answer ?</p> <div style="display: flex; align-items: center;"> <div style="flex: 1; border-bottom: 1px solid gray; position: relative;"> <div style="position: absolute; left: 0; bottom: -2px;">Unconfident</div> <div style="position: absolute; right: 0; bottom: -2px;">Confident</div> <div style="width: 50%; height: 5px; background: linear-gradient(to right, blue, gray);"></div> </div> <div style="margin-left: 5px;"> <div style="width: 10px; height: 10px; background-color: blue; border-radius: 50%;"></div> </div> </div> <p style="text-align: center;">1 2 3 4 5</p> </div> </div> <p style="text-align: right;"><input type="button" value="Next"/></p>	/
End	

approach defined by European Telecommunications Standards Institute for evaluating the pictogram [155], the understandability can be investigated in the multiple tiers, including whether the subject is able to give an interpretation on the pictogram or not, whether the given interpretation is correct or wrong, and whether the given interpretation is with certainty or not. It is mentioned in this approach that a wrong interpretation may be more dangerous than no interpretation depending on the usage context. Moreover, if the users are extremely uncertain about their interpretation, they may decide to not make any next action. These considerations can be well explained in the scope of interactions between road users. In the case where the pedestrian cannot confirm the vehicle intention, it is observed that they generally tended to stay at the curb and hesitated to cross [27]. T. Ben-Bassat and D. Shinar [156] observed a “wrong but sure” situation where the drivers completely misinterpreted the road signs, but they still make a fast reaction without realizing the mistake. These misinterpretations are extremely dangerous, as it may result in errors leading to safety issues [157]. Taking account of these, we decided to evaluate the understandability in this study by the indicators in a wide range, including not only the correctness rate, but also the interpretation rate, the variation of subjective certainties, as well as the distribution of interpretation categories.

Interpretation rate (IR) is the percentage of given interpretations among the number of subjects with regard to the signal design. This first indicator of understandability represents in how many instances subjects are able to give their interpretations on the signal design, because they think that they have understood the signal design. In the coding process, if the subject in the test selected “I understand”, and gave a written interpretation, the number of interpretations was incremented by one. In this study, this indicator is used to evaluate the understandability of the signal design in the aspect of interpretability.

Correctness rate (CR) is the percentage of correct interpretations on the signal meaning among all given interpretations with regard to the signal design. This second and most important indicator represents in how many instances subjects can correctly interpret the signal design as its intended meaning. In the coding process, the correctness was manually assessed according to the interpretation written by the subject. If the signal design was correctly interpreted as the vehicle yielding intention, no matter the advice, information, or cooperation message, the number of correct interpretations was incremented by one. If not, the number of confusion was incremented by one. In this study, this indicator is used to evaluate the understandability of the signal design in the aspect of interpretation correctness.

Variation of subjective certainties (SCs) is the variation of certainty degrees about given interpretations subjectively rated by subjects with regard to the signal design. This third indicator represents how certain subjects are about their interpretations on the signal design. The account of this indicator is based on the consideration that low certainties about interpretations on extended signals may cause longtime hesitation in AV2P communications. In this study, this indicator is used to evaluate the understandability of the signal design in the aspect of interpretation certainty.

Distribution of interpretation categories is the proportions of different interpretation categories with regard to the signal design. It includes the correct interpretation of yielding intention and the different types of confusion. While assessing the correctness of interpretation on the signal design, all interpretations other than the yielding intention were coded as confusion. We classified confusion into the different types, and calculated their proportions along with that of

the yielding intention. In this study, it is expected that this indicator would be useful for investigating the reason of different types of confusion.

According to the subjects' responses recorded in the monitored-based online tests, the above four indicators for each signal design were calculated to represent their individual understandability (see Fig. 3.4). Furthermore, with the objective of evaluating the understandability depending on the signal form and the content type (for the pictogram), the mean IR, the mean CR, the global variation of SCs, and the global distribution of interpretation

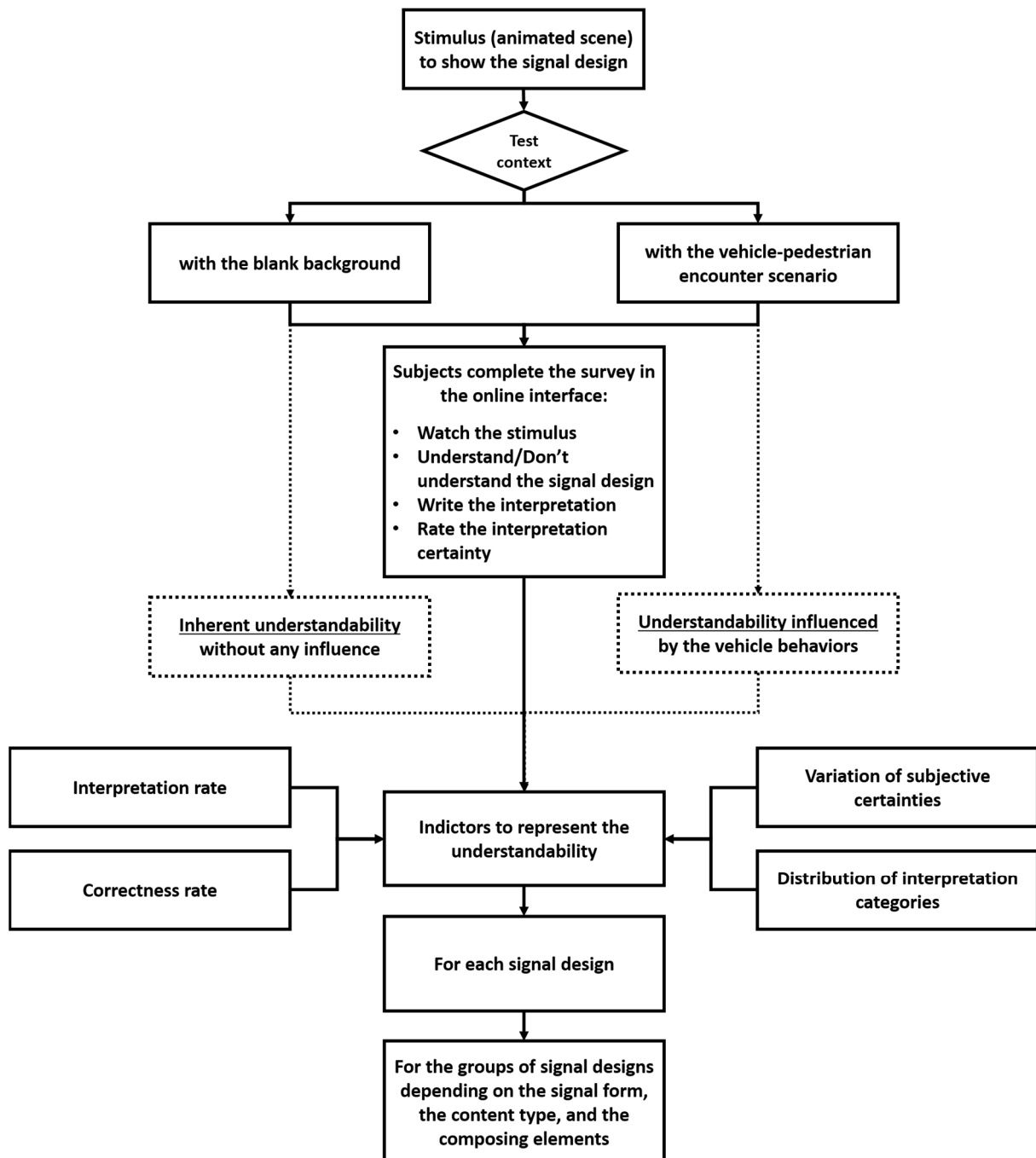


Fig. 3.4 Global view of the method which is used to evaluate the understandability of each signal design and depending on the signal form, the content type, and the composing elements.

categories were calculated with the groups of light patterns, advice pictograms, information pictograms, and cooperation pictograms. To study the understandability depending on the composing elements, the mean IR, the mean CR, and the global variation of SCs were calculated with the groups of light patterns differing in motion and color, and with the groups of pictograms differing in existence or absence of actor figure, action symbol, field figure, and color. Additionally, in order to test statistically the significant difference of understandability depending on the signal form, the content type, and the composing elements (predictor variable), the logistic regressions were carried out with regard to IR and CR, whose data were logistically coded (response variable). The ordinal logistic regressions were carried out with regard to SC, whose data were ordinally rated (response variable). For example, in the logistic regression with regard to IR depending on the signal form and the content type, the response variable (giving/not giving an interpretation) was associated with the predictor variable (light pattern/advice pictogram/information pictogram/cooperation pictogram). In the logistic regression with regard to CR depending on the composing elements for the light pattern, the response variable (correct interpretation/confusion) was associated with the sum of the first predictor variable (conventional blink/double fast blink/alternating blink/round-trip sweeping/breath-effect) and the second predictor variable (white/cyan/bi-color). In the ordinal logistic regression with regard to SC depending on the signal form and the content type, the response variable (certainty degree 1/2/3/4/5) was associated with the predictor variable (light pattern/advice pictogram/information pictogram/cooperation pictogram).

3.5 Test Results

A total of 516 subjects participated in the online tests. For each of the forty-nine signal designs, 5-6 different subjects participated in the tests with the blank background and other 5-6 different subjects participated in the tests with the vehicle-pedestrian encounter scenario around the crosswalk. 4 subjects who selected “I understand” the signal meaning but wrote “I do not know”, “I do not understand”, or “I misclicked” were excluded. The 512 remaining subjects were from sixteen countries, with the three most represented countries being France, Great Britain, and China. These subjects were composed of 344 males and 168 females, among which 82% had the driver license. The distribution of subjects’ age groups was: 0-18 (0.8%), 18-24 (46.5%), 24-34 (25.8%), 34-44 (9.3%), 44-54 (11.1%), and 54-74 (6.5%) years old. As a result, the understandability of each signal design is illustrated in Table 3.3 and Table 3.4, which provide us an initial view on their performance and problems. Moreover, the understandability depending on the signal form and the content type is illustrated in Fig. 3.5, Fig. 3.6, and Table 3.6. The understandability depending on the composing elements is illustrated in Fig. 3.7 to Fig. 3.12. The results of the statistical tests are listed in Table 3.7. These results allow us to make a further comparison among the light patterns and the three types of pictograms, as well as carry out an analysis on the effects of their composing elements.

3.5.1 Understandability of Each Signal Design

Table 3.4 and Table 3.5 present the understandability of each signal design (fifteen light patterns,

Table 3.3 Understandability of each signal design tested with the blank background

N°	Design	IR (%)	CR (%)	Variation of SCs (nb of the subjects)					Distribution of interpretation categories (%)					
				1	2	3	4	5	Yielding	Warning	Turning	Notification Crosswalk	Awareness Pedestrian	Others
01		60.0	33.3	0	1	1	0	1	33.3	33.3	0	0	0	33.3
02		80.0	0	0	0	1	1	2	0	100	0	0	0	0
03		100	0	0	0	0	3	2	0	80.0	0	0	0	20.0
04		60.0	0	0	0	3	0	0	0	33.3	0	0	0	66.7
05		80.0	25.0	0	2	1	1	0	25.0	75.0	0	0	0	0
06		40.0	0	0	0	1	1	0	0	100	0	0	0	0
07		20.0	0	0	1	0	0	0	0	100	0	0	0	0
08		40.0	0	0	0	1	1	0	0	100	0	0	0	0
09		40.0	0	0	0	1	1	0	0	50.0	50.0	0	0	0
10		20.0	0	0	0	0	1	0	0	100	0	0	0	0
11		40.0	0	0	0	1	0	1	0	100	0	0	0	0
12		60.0	33.3	0	0	1	2	0	33.3	66.7	0	0	0	0
13		60.0	0	0	1	2	0	0	0	100	0	0	0	0
14		40.0	0	0	0	2	0	0	0	50.0	0	0	0	50.0
15		20.0	0	0	0	1	0	0	0	0	0	0	0	100
16		60.0	66.7	0	0	1	1	1	66.7	0	0	0	33.3	0
17		83.3	60.0	0	1	0	2	2	60.0	0	0	0	40.0	0
18		100	20.0	0	1	3	0	1	20.0	0	60.0	0	20.0	0
19		80.0	75.0	0	0	1	0	3	75.0	0	0	25.0	0	0
20		100	33.3	0	1	1	2	2	33.3	0	0	50.0	0	16.7
21		40.0	0	0	0	1	1	0	0	0	0	0	100	0
22		80.0	75.0	0	0	1	3	0	75.0	0	0	0	0	25.0
23		100	0	0	0	1	2	2	0	0	100	0	0	0
24		60.0	0	0	0	1	0	2	0	0	100	0	0	0
25		60.0	0	0	0	1	0	2	0	0	0	100	0	0
26		80.0	100	0	0	1	3	0	100	0	0	0	0	0
27		20.0	100	0	0	0	1	0	100	0	0	0	0	0
28		20.0	100	0	0	0	1	0	100	0	0	0	0	0
29		80.0	75.0	0	1	1	2	0	75.0	0	0	25.0	0	0
30		50.0	66.7	0	0	2	0	1	66.6	0	0	33.3	0	0
31		80.0	0	0	1	0	3	0	0	0	0	75.0	0	25.0
32		80.0	75.0	0	0	2	2	0	75.0	0	0	25.0	0	0
33		50.0	66.7	0	1	1	0	1	66.7	0	0	0	0	33.3
34		0	/	/	/	/	/	/	/	/	/	/	/	/
35		0	/	/	/	/	/	/	/	/	/	/	/	/
36		0	/	/	/	/	/	/	/	/	/	/	/	/
37		0	/	/	/	/	/	/	/	/	/	/	/	/
38		16.7	0	0	1	0	0	0	0	0	0	0	0	100
39		20.0	100	1	0	0	0	0	100	0	0	0	0	0
40		16.7	100	0	0	0	0	1	100	0	0	0	0	0
41		83.3	100	0	1	2	1	1	100	0	0	0	0	0
42		33.3	50.0	0	0	1	1	0	50.0	0	0	0	50.0	0
43		60.0	100	0	0	1	1	1	100	0	0	0	0	0
44		100	80.0	0	0	1	1	3	80.0	20	0	0	0	0
45		83.3	60.0	0	1	0	2	2	60.0	0	20.0	0	0	20.0
46		40.0	0	0	0	0	2	0	0	0	100	0	0	0
47		60.0	33.3	0	1	1	1	0	33.3	33.3	0	0	33.3	0
48		60.0	33.3	0	0	2	0	1	33.3	0	0	33.3	33.3	0
49		40.0	50.0	0	0	1	1	0	50.0	0	0	0	50.0	0

Table 3.4 Understandability of each signal design tested with the vehicle-pedestrian encounter scenario

N°	Design	IR (%)	CR (%)	Variation of SCs (nb of the subjects)					Distribution of interpretation categories (%)					
				1	2	3	4	5	Yielding	Warning	Turning	Notification Crosswalk	Awareness Pedestrian	Others
01		80.0	75.0	0	0	1	0	3	75.0	25.0	0	0	0	0
02		100	80.0	0	0	0	4	1	80.0	20.0	0	0	0	0
03		100	40.0	0	0	1	3	1	40.0	40.0	0	0	0	20.0
04		100	100	0	0	2	1	2	100	0	0	0	0	0
05		40.0	100	0	0	0	0	2	100	0	0	0	0	0
06		60.0	100	0	1	1	1	0	100	0	0	0	0	0
07		40.0	100	0	0	1	0	1	100	0	0	0	0	0
08		60.0	100	0	0	0	2	1	100	0	0	0	0	0
09		40.0	100	0	0	0	1	1	100	0	0	0	0	0
10		80.0	50.0	0	0	2	2	0	50.0	25.0	25.0	0	0	0
11		80.0	75.0	0	1	3	0	0	75.0	25.0	0	0	0	0
12		80.0	75.0	0	0	1	2	1	75.0	25.0	0	0	0	0
13		100	80.0	0	0	0	3	2	80.0	20.0	0	0	0	0
14		60.0	100	0	0	0	2	1	100	0	0	0	0	0
15		80.0	75.0	0	0	1	3	0	75.0	0	0	25.0	0	0
16		83.3	60.0	0	1	0	2	2	60.0	0	20.0	0	20.0	0
17		83.3	80.0	0	1	0	1	3	80.0	0	0	20.0	0	0
18		80.0	75.0	0	0	1	1	2	75.0	0	20.0	0	0	0
19		100	40.0	0	0	1	3	1	40.0	0	0	60.0	0	0
20		100	40.0	0	0	0	2	3	40.0	0	0	20.0	40.0	0
21		83.3	100	0	0	0	1	4	100	0	0	0	0	0
22		80.0	100	0	0	0	1	3	100	0	0	0	0	0
23		80.0	25.0	0	1	0	0	3	25.0	0	75.0	0	0	0
24		100	40.0	0	0	1	2	2	40.0	0	60.0	0	0	0
25		100	20.0	0	0	0	2	3	20.0	0	0	40.0	40.0	0
26		80.0	75.0	0	0	0	1	3	75.0	0	0	0	25.0	0
27		100	42.9	0	0	1	3	3	42.9	0	42.9	0	0	14.3
28		83.3	80.0	1	0	1	3	0	100	0	0	0	0	0
29		100	40.0	0	0	0	3	2	40.0	0	0	60.0	0	0
30		100	60.0	0	0	0	1	4	60.0	0	0	40.0	0	0
31		100	60.0	0	0	1	2	2	60.0	0	0	40.0	0	0
32		100	40.0	0	0	0	3	2	40.0	0	0	60.0	0	0
33		100	100	0	1	1	2	1	100	0	0	0	0	0
34		100	40.0	0	1	2	2	0	40.0	0	0	60.0	0	0
35		60.0	33.3	0	0	1	0	2	33.3	0	0	33.3	0	33.3
36		80.0	75.0	0	0	0	1	3	75.0	0	0	25.0	0	0
37		60.0	100	0	0	2	0	1	100	0	0	0	0	0
38		0	/	/	/	/	/	/	/	/	/	/	/	/
39		60.0	66.7	0	0	0	2	1	66.7	0	0	0	0	33.3
40		66.7	75.0	0	0	0	1	3	75.0	0	0	0	0	25.0
41		100	100	0	0	1	2	2	100	0	0	0	0	0
42		100	60.0	0	0	1	2	2	60.0	0	0	0	20.0	20.0
43		60.0	33.3	1	0	0	0	2	33.3	0	66.7	0	0	0
44		100	100	0	0	1	1	3	100	0	0	0	0	0
45		83.3	100	0	0	0	2	3	100	0	0	0	0	0
46		83.3	60.0	0	1	0	3	1	60.0	0	40.0	0	0	0
47		100	100	0	0	0	2	3	100	0	0	0	0	0
48		40.0	0	0	0	0	1	1	0	0	100	0	0	0
49		85.7	83.3	0	0	1	3	2	83.3	0	0	0	0	0

Table 3.5 Interpretation categories composed of the yielding intention and the different types of confusion, and examples of the recorded subjects' interpretations

Interpretation categories	Examples of subjects' interpretations
<i>Yielding intention</i>	<i>"The vehicle stops and lets the people to cross"</i> <i>"That I can cross the road"</i>
<i>Warning message</i>	<i>"Warning"</i> <i>"Warning, be careful"</i>
<i>Turning intention</i>	<i>"The vehicle is going to turn to its left"</i> <i>"Turning to the right"</i>
<i>Notification of the crosswalk</i>	<i>"indicate a crosswalk near"</i> <i>"There's a pedestrian crossing ahead"</i>
<i>Vehicle awareness of the pedestrian</i>	<i>"The vehicle has detected a pedestrian"</i> <i>"There are pedestrians in front of the vehicle"</i>
<i>Others</i>	<i>"Immobilization of the vehicle"</i> <i>"Charging the vehicle"</i>

thirteen advice pictograms, thirteen information pictograms, eight cooperation pictograms) tested with the blank background and with the encounter scenario around the crosswalk in terms of the IR, the CR, the variation of SCs, and the distribution of interpretation categories. The examples of the recorded subjects' interpretations, including the correct interpretation of yielding intention and the different types of confusion were shown in Table 3.5. We highlighted the noteworthy results, including the low ($< 33.3\%$), medium ($> 33.3\%$ and $< 66.6\%$), high ($> 66.6\%$) IR and CR, the median SC, and the confusion related to the signal design with the low CR.

It can be observed that, with the blank background, most of the light patterns had medium IRs. The light patterns N°02, 03, 05 (conventional blink in cyan, conventional blink in bi-color, double fast blink in cyan) had the high IRs. On the contrary, the light patterns N°07, 10, 15 (alternating blink in white, round-trip sweeping in white, breath-effect in bi-color) had the low IRs. Notably, all the light patterns had low CRs and we observed a lot of confusion, like *"Warning"*, and *"Be careful"*. As regards such confusion, we categorized them into the *warning message*. Moreover, some unusual confusion was observed with few light patterns, for example, the light patterns N°01, 15 (conventional blink in white, breath-effect in bi-color) could be misinterpreted as *"immobilization of the vehicle"* and *"charging the vehicle"*. Considering their irregularity and limited number, we gathered them in a category named *others* which would not be further demonstrated and studied. Besides, the median SCs about the given interpretations for the light patterns were between 2 and 4.

For the advice pictograms, most of them had medium and high IRs, but only a part of them had medium and high CRs. Notably, two advice pictograms N°27, 28 (both contain a figure of a pair of feet to represent the pedestrian in semantically distant way) had the low IRs but the high CRs. Furthermore, it is observed that the advice pictograms N°18, 20, 21, 23, 24, 25 had the low CRs. Concerning the confusion related to them, we observed that the advice pictograms N°18, 23, 24 (a white arrow symbol with a crosswalk figure, a white arrow symbol, a green arrow symbol) could be misinterpreted as, for example *"The vehicle is going to turn to its left"*, and *"Turning to the right"*. Such confusion was categorized into the *turning intention*.

Especially for the advice pictogram N°23, its IR reached 100%. However, its CR was 0% and with a high median SC as 4. This pictogram was found to be confidently misinterpreted as the *turning intention*. Moreover, it is noticed that the confusion, like “*indicate a crosswalk near*”, and “*there’s a pedestrian crossing ahead*” could happen with the advice pictograms N°20, 25 (a green pedestrian figure with a crosswalk figure, a white pedestrian figure). Such confusion was categorized into the *notification of the crosswalk*. In addition, we observed, for example, “*the vehicle has detected a pedestrian*” and “*there are pedestrians in front of the vehicle*” with the advice pictograms N°18, 21 (a white arrow symbol with a crosswalk figure, a white pedestrian figure with a white arrow symbol). Such confusion was gathered into a category named *vehicle awareness of the pedestrian*. Besides, the median SCs for the advice pictograms were between 3 and 5.

For the information pictograms, most of them had low IRs. Especially for the information pictograms N°34, 35, 36, 37 (all contain a dotted line symbol or a combination of a dotted line symbol with a vehicle figure), their IRs were 0%. This represents that no subject was able to give an interpretation on these pictograms during the tests. Apart from them, most of the information pictograms had medium and high CRs. Besides, the median SCs for the information pictograms were between 1 and 5. Notably, the CR and the median SC for the information pictogram N°31 (a white dotted line symbol with a crosswalk figure) were 0% and 4, as it is observed to be largely misinterpreted as the *notification of the crosswalk*.

For the cooperation pictograms, all of them had medium and high IRs and most of them had medium and high CRs. There were three cooperation pictograms N°46, 47, 48 which had the low CRs. We observed that the pictogram N°46 (two arrow symbols with the opposite colors) was largely misinterpreted as the *turning intention*. The pictogram N°47 (a vehicle figure and a pedestrian figure with the opposite colors) could be misinterpreted as the *warning message* or the *vehicle awareness of the pedestrian*. The pictogram N°48 (two semantically distant actor figures and two action symbols with the opposite colors) could be misinterpreted as the *notification of the crosswalk* or the *vehicle awareness of the pedestrian*. Besides, the median SCs for the cooperation pictograms were between 3 and 5.

With the vehicle-pedestrian encounter scenario around the crosswalk, it is noticed that all the light patterns had medium and high IRs and CRs. The median SCs for them were between 3 and 5. Notably, the light pattern N°04 (double fast blink in white) got 100% of IR and CR with a high median SC as 4.

For the advice pictograms, all of them had high IRs, and most of them had medium and high CRs. Like what was observed with the blank background, the advice pictogram N°23 (a white arrow symbol) had a low CR with a high median SC as 5. This pictogram could be largely misinterpreted as the *turning intention*. Also, the confusion about *turning intention* could happen with the pictogram N°27 (a figure of a pair of feet with a white arrow symbol). Moreover, it is found that the pictogram N°25 (a white pedestrian figure) could be misinterpreted as the *notification of the crosswalk* or the *vehicle awareness of the pedestrian*. Besides, the median SCs for the advice pictograms were between 4 and 5.

For the information pictograms, only the pictogram N°38 (a white vehicle figure) had 0% of IR and all the other information pictograms had medium and high IRs. In terms of CR, all the information pictograms had medium and high CRs except for the pictogram N°35 (a white vehicle figure with a red dotted line symbol). It is observed that this pictogram could be

misinterpreted as the *notification of the crosswalk*. Besides, the median SCs for the information pictograms were between 3 and 5. It is noteworthy that the pictogram N°33 (a red vehicle figure with a crosswalk figure) got 100% of IR and CR with a high median SC as 4. The pictogram N°41 (a figure of a foot with a pedal) also got 100% of IR and CR with a high median SC as 5.

For the cooperation pictograms, all of them had medium and high IRs and most of them had medium and high CRs. It is observed that the pictogram N°43 (a crosswalk figure and two action symbols with the opposite colors) could be misinterpreted as the *turning intention*. This confusion about *turning intention* also happened with the pictogram N°48 (two semantically distant actor figures and two action symbols with the opposite colors). Besides, the median SCs for the cooperation pictograms were between 4 and 5. Notably, the pictogram N°44 (two actor figures with the opposite colors and a crosswalk figure) got 100% of IR and CR with a high SC of 5. The pictogram N°47 (two actor figures with the opposite colors) also got 100% of IR and CR with a high median SC as 5.

In order to be commonly used, a signal must reach a certain level of understandability, especially when the conveyed information is related to safety. According to ISO 9186-1989 [158], a public information sign is acceptable if 67% of the users understand its meaning in an unquestionable way. According to *American National Standard Institute (ANSI) Z535-1987* [159], a sign must be understood by over 85% of the users in order to be standardized. As regards the signal designs tested in this study, the acceptable ones can be identified by evaluating the product of IR and CR. This product represents in how many instances subjects are able to give their interpretations on the signal design and the given interpretations are correct. By respecting the above ISO standard, we identified that the acceptable signal designs involve N°26, 41, 44 with the blank background and involved N°02, 04, 13, 21, 22, 33, 41, 44, 45, 47, 49 with the vehicle-pedestrian encounter scenario around the crosswalk. By respecting the ANSI standard, no acceptable signal design was found with the blank background. With the encounter scenario, N°04, 33, 41, 44, 47 are the acceptable signal designs.

3.5.2 Understandability depending on the Signal Form and the Content Type

In order to have the comparisons among the light patterns, the advice pictograms, the information pictograms, and the cooperation pictograms, we can see Fig. 3.5, Fig. 3.6, and Table 3.6 which illustrate the understandability depending on the signal form and the content type in terms of the IR, the CR, the variation of SCs, and the distribution of interpretation categories. Table 3.7 shows the data of the statistical tests for finding the significant differences.

It is notable that, with the blank background, the light patterns (IR: 50.6%, CR: 7.9%) had a much lower CR than each of the advice pictograms, the information pictograms, and the cooperation pictograms. The statistical tests further reveal that these differences of CR ($p < 0.01$) were significant. Moreover, the light patterns had a higher IR than the information pictograms, but a lower IR than the advice pictograms and the cooperation pictograms. The significant difference of IR ($p < 0.05$) for the light patterns was found only as compared to the advice pictograms. For the information pictograms (IR: 36.6%, CR: 65.4%), even though their CR was the highest, they had a lower IR than each of the light patterns, the advice pictograms,

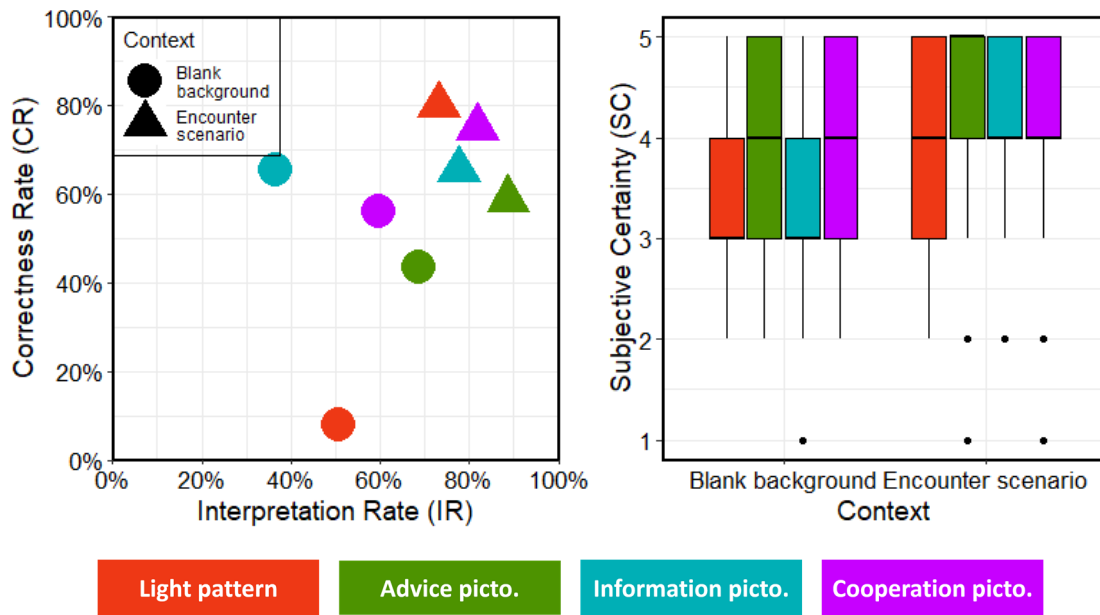


Fig. 3.5 Understandability depending on the signal form and the content type (light pattern, advice pictogram, information pictogram, cooperation pictogram), in terms of the interpretation rate, and the correctness rate, and the variation of subjective certainties.

and the cooperation pictograms. The significant differences of their IR ($p < 0.05$) were found as compared to the advice pictograms and the cooperation pictograms. No significant difference of their CR was found as compared to the others. Between the advice pictograms (IR: 68.7%, CR: 43.5%) and the cooperation pictograms (IR: 59.5%, CR: 56.0%), the differences of IR and CR were found to be not significant. The median SCs for the light patterns and the information pictograms were 3, whereas those for the advice pictograms and the cooperation pictograms were 4. The statistical tests reveal that the significant difference of SC ($p < 0.05$) existed for the advice pictograms as compared to the light patterns.

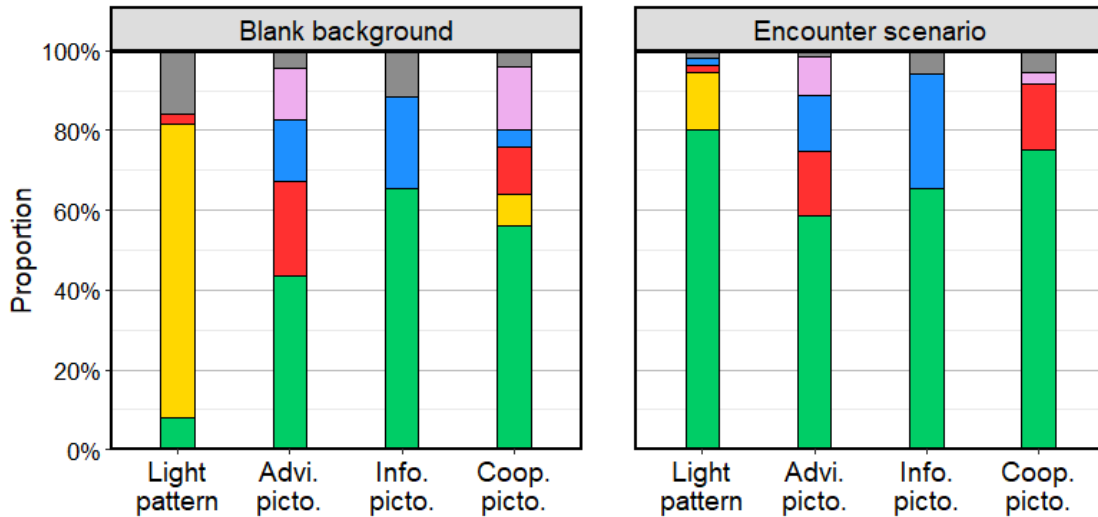
With the vehicle-pedestrian encounter scenario around the crosswalk, it is noticed that the IRs and CRs for the light patterns (IR: 73.3%, CR: 80.0%), the advice pictograms (IR: 88.7%, CR: 58.7%), the information pictograms (IR: 77.6%, CR: 65.4%), and the cooperation pictograms (IR: 81.8%, CR: 75.0%) increased to higher levels as compared to those observed with the blank background. Especially, a considerable increase of CR was observed for the light patterns, even being higher than the three types of pictograms. For the light patterns, their CR ($p < 0.05$) was found to be significantly higher than that of the advice pictograms. Still, their IR ($p < 0.05$) was significantly lower than that of the advice pictograms. Among the three types of pictograms, the differences of IR and CR were found to be not significant in the statistical tests. The median SC for the advice pictograms reached 5, whereas those for the light patterns, the information pictograms and the cooperation pictograms were 4. The significant difference of SC ($p < 0.05$) was found only between the light patterns and the advice pictograms.

Fig. 3.6 and Table 3.6 present the understandability depending on the signal form and the content type in terms of the distribution of interpretation categories. The interpretation categories are composed of the correct interpretation of yielding intention and the different types of confusion. The signal designs involved in each type of confusion are listed and illustrated as well. With the blank background, it is observed that the *warning message* was the

Table 3.7 Statistical data of the interpretation rate, the correctness rate, and the subjective certainty depending on the signal form, the content type, and the composing elements, calculated by the logistic and ordinal logistic regressions

Difference	Context	Interpretation Rate (IR)			Correctness Rate (CR)			Subjective Certainty (SC)		
		exp ⁻¹ (or)	z-score	p-value	exp ⁻¹ (or)	z-score	p-value	exp ⁻¹ (or)	t-score	p-value
Signal form and content type										
Advice pictograms:	Blank	0.76	2.16	0.0306	2.19	3.27	0.0011	0.80	2.00	0.0445
Light patterns	Encounter	1.05	2.30	0.0214	-1.03	-2.44	0.0146	0.83	2.38	0.0173
Information pictograms:	Blank	-0.58	-1.70	0.0885	3.09	4.24	<0.0001	-0.18	-0.38	0.7047
Light patterns	Encounter	0.23	0.59	0.5552	-0.75	-1.68	0.0923	0.56	1.55	0.1214
Cooperation pictograms:	Blank	0.36	0.92	0.3574	2.70	3.73	0.0002	0.71	1.52	0.1290
Light patterns	Encounter	0.49	1.05	0.2948	-0.29	-0.56	0.5739	0.73	1.81	0.0702
Information pictograms:	Blank	-1.33	-3.70	0.0002	0.90	1.77	0.0772	-0.98	-2.13	0.0332
Advice pictograms	Encounter	-0.82	-1.72	0.0849	0.28	0.73	0.4654	-0.27	-0.76	0.4453
Cooperation pictograms:	Blank	-0.40	-0.97	0.3312	0.50	1.00	0.3147	-0.09	-0.21	0.8349
Advice pictograms	Encounter	-0.56	-1.03	0.3017	0.75	1.61	0.1066	-0.10	-0.26	0.7970
Cooperation pictograms:	Blank	0.93	2.34	0.0193	-0.39	-0.69	0.4934	0.89	1.71	0.0881
Information pictograms	Encounter	0.26	0.53	0.5933	0.46	0.96	0.3380	0.17	0.42	0.6763
Composing elements (motion and color) for the light pattern										
Double fast blinks:	Blank	-0.99	-1.18	0.2367	0.27	0.18	0.8576	-2.49	-2.53	0.0114
Conventional blinks	Encounter	-1.97	-1.67	0.0943	19.11	0.00	0.9950	-0.82	-0.94	0.3459
Alternating blinks:	Blank	-2.10	-2.47	0.0136	-17.14	0.00	0.9971	-2.25	-2.07	0.0380
Conventional blinks	Encounter	-2.81	-2.42	0.0157	18.93	0.00	0.9960	0.21	0.24	0.8114
Round-trip sweepings:	Blank	-1.81	-2.16	0.0307	0.84	0.55	0.5830	-0.76	-0.78	0.4325
Conventional blinks	Encounter	-1.26	-1.03	0.3021	0.13	0.15	0.8830	-2.05	-2.59	0.0096
Breath-effects:	Blank	-1.81	-2.16	0.0307	-17.29	0.00	0.9968	-2.83	-2.60	0.0093
Conventional blinks	Encounter	-1.26	-1.03	0.3021	1.14	1.17	0.2440	-0.27	-0.38	0.7042
Alternating blinks:	Blank	-1.11	-1.45	0.1460	-17.41	0.00	0.9970	0.24	0.22	0.8280
Double fast blinks	Encounter	-0.85	-1.11	0.2678	-0.18	0.00	1.0000	1.03	1.00	0.3174
Round-trip sweepings:	Blank	-0.82	-1.10	0.2740	0.57	0.36	0.7190	1.72	1.61	0.1078
Double fast blinks	Encounter	0.71	0.83	0.4091	-18.99	0.00	0.9950	-1.23	-1.38	0.1670
Breath-effects:	Blank	-0.82	-1.10	0.2740	-17.57	0.00	0.9970	-0.34	-0.34	0.7336
Double fast blinks	Encounter	0.71	0.83	0.4091	-17.97	0.00	0.9960	0.54	0.64	0.5239
Round-trip sweepings:	Blank	0.29	0.38	0.7034	17.98	0.00	0.9970	1.49	1.27	0.2026
Alternating blinks	Encounter	1.55	1.85	0.0639	-18.81	0.00	0.9960	-2.26	-2.34	0.0191
Breath-effects:	Blank	0.29	0.38	0.7034	-0.15	0.00	1.0000	-0.58	-0.49	0.6218
Alternating blinks	Encounter	1.55	1.85	0.0639	-17.79	0.00	0.9960	-0.48	-0.54	0.5921
Breath-effects:	Blank	0.00	0.00	1.0000	-18.13	0.00	0.9970	-2.06	-1.77	0.0769
Round-trip sweepings	Encounter	0.00	0.00	1.0000	1.02	1.01	0.3130	1.77	2.26	0.0236
Cyans:	Blank	0.55	0.90	0.3676	-0.46	-0.30	0.7641	1.07	1.26	0.2080
Whites	Encounter	-0.73	-1.03	0.3049	0.96	0.96	0.3390	-0.49	-0.75	0.4509
Bi-color:	Blank	0.37	0.60	0.5461	-0.50	-0.32	0.7480	1.49	1.71	0.0880
Whites	Encounter	-0.50	-0.70	0.4816	-0.27	-0.32	0.7480	-0.79	-1.25	0.2131
Bi-color:	Blank	-0.18	-0.30	0.7630	-0.05	-0.03	0.9765	0.42	0.56	0.5777
Cyans	Encounter	0.22	0.33	0.7397	-1.24	-1.26	0.2080	-0.30	-0.48	0.6330
Composing elements (existence or absence of actor figure, action symbol, field figure, and color) for the pictogram										
With the actor figure (direct):	Blank	-0.29	-0.62	0.5380	1.69	2.43	0.0153	-0.18	-0.35	0.7244
Without the actor figure	Encounter	0.12	0.23	0.8211	0.23	0.50	0.6190	0.54	1.20	0.2295
With the actor figure (semantically distant):	Blank	-0.36	-0.63	0.5284	3.16	3.21	0.0013	-0.18	-0.24	0.8084
Without the actor figure	Encounter	0.32	0.48	0.630	0.36	0.58	0.5620	0.04	0.07	0.9449
With the actor figure (semantically distant):	Blank	-0.07	-0.15	0.8822	1.47	1.81	0.0697	0.01	0.01	0.9930
With the actor figure (direct):	Encounter	0.19	0.34	0.7318	0.12	0.22	0.8220	-0.50	-1.05	0.2945
With the action symbol:	Blank	-0.72	-1.86	0.0628	-0.13	-0.27	0.7907	0.02	0.05	0.9608
Without the action symbol	Encounter	-0.08	-0.16	0.8730	-0.28	-0.70	0.4860	0.35	1.01	0.3128
With the field figure:	Blank	1.52	3.84	0.0001	0.87	1.71	0.0865	0.12	0.29	0.7750
Without the field figure	Encounter	1.35	2.50	0.0124	-0.27	-0.68	0.4960	-0.23	-0.64	0.5204
With green color:	Blank	1.47	2.50	0.0125	0.38	0.61	0.5416	0.51	1.00	0.3192
With white color	Encounter	0.40	0.56	0.5774	0.35	0.68	0.4980	0.56	1.13	0.2597
With red color:	Blank	-1.43	-2.61	0.0091	0.59	0.63	0.5275	-1.00	-1.17	0.2427
With white color	Encounter	-0.51	-0.85	0.3953	0.76	1.28	0.2010	-0.20	-0.40	0.6923
With green opposite red:	Blank	0.37	0.90	0.3679	0.39	0.67	0.5004	0.35	0.75	0.4533
With white color	Encounter	-0.13	-0.27	0.7908	0.78	1.69	0.0910	0.11	0.29	0.7715

or is the odds ratio, which represents the effect size of the predictor; z-score and t-score are the ratio of the regression coefficient divided by the standard error, which describe the position of a raw score in terms of its distance from the mean.



Interpretation categories: see Table 3.6

Fig. 3.6 Understandability depending on the signal form and the content type (light pattern, advice pictogram, information pictogram, cooperation pictogram), in terms of the distribution of interpretation categories.

Table 3.6 Interpretation categories composed of the yielding intention and the different types of confusion, and signal designs involved in the confusion

Legends	Categories	Signal designs involved in the confusion		Illustration
		Blank background	Encounter scenario	
	<i>Yielding intention</i>	/	/	/
	<i>Warning message</i>	N°1-15, 44, 47	N°1, 3, 10-13	∇ Light patterns
	<i>Turning intention</i>	N°18, 23, 24, 46	N°18, 23, 24, 27, 43, 46, 48	
	<i>Notification of the crosswalk</i>	N°19, 20, 25, 29-32, 44	N°17, 19, 20, 25, 29-32, 34-36	
	<i>Vehicle awareness of the pedestrian</i>	N°16, 17, 21, 42, 47	N°16, 20, 25, 26, 42	
	<i>Others</i>	N°1-3, 20, 22, 31, 33, 38, 45	N°5, 27, 35, 39, 40, 42, 49	Not explored

main type of confusion for the light patterns. For the advice pictograms, the *turning intention*, the *notification of the crosswalk*, and the *vehicle awareness of the pedestrian* were the three main types of confusion. Regarding the information pictograms, the *notification of the crosswalk* was the main type of confusion. For the cooperation pictograms, all the types of confusion were observed: *warning message*, *turning intention*, *notification of the crosswalk*, and *vehicle awareness of the pedestrian*.

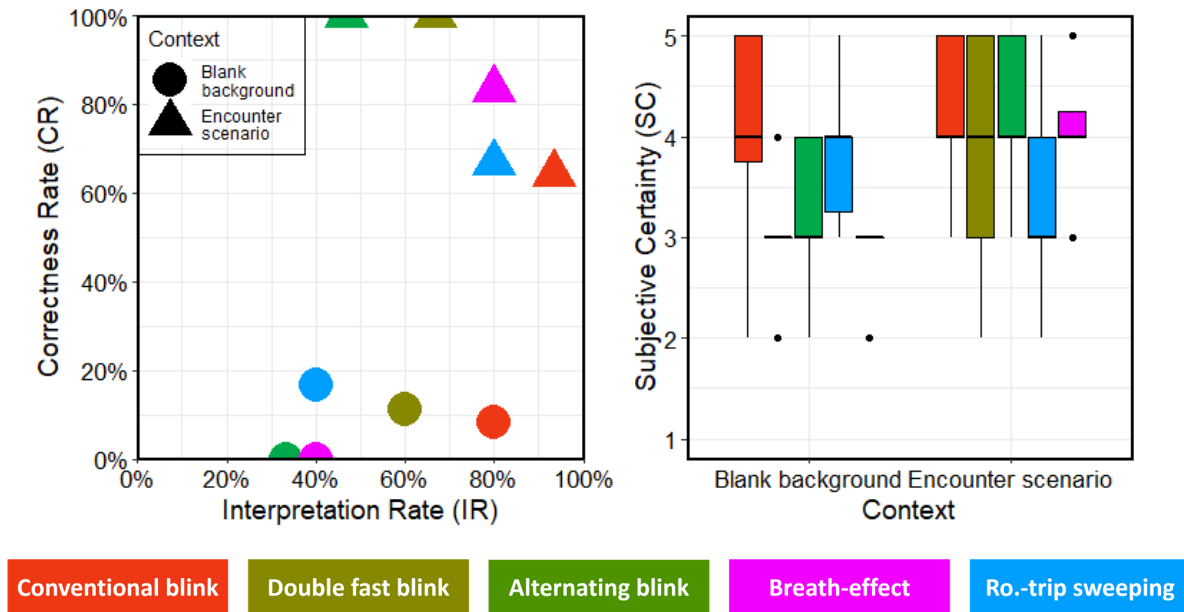


Fig. 3.7 Understandability depending on the motion for the light pattern, in terms of the interpretation rate, the correctness rate, and the variation of subjective certainties.

With the encounter scenario, it is noticed that, for the light patterns, the proportion of *warning message* became smaller, alongside a big proportion of correct interpretation of *yielding intention*. For the advice pictograms, the main types of confusion were the same as those observed with the blank background. Regarding the information pictograms, the main type of confusion was the *notification of the crosswalk*. For the cooperation pictograms, the diversity of confusion disappeared, and the *turning intention* was the main type of confusion. A category of *others* gathered some unusual confusion, which was not further explored.

3.5.3 Understandability depending on the Composing Elements

3.5.3.1 Motion and Color for the Light Pattern

Fig. 3.7 and Fig. 3.8 associated with Table 3.7 present the understandability depending on the motion and the color for the light pattern.

Concerning the motion, with the blank background, the conventional blinks (IR: 80.0%, CR: 8.3%) had a higher IR than the four other motions. The significant differences of their IR ($p < 0.05$) were found as compared to each of the alternating blinks (IR: 33.3%, CR: 0.0%), the round-trip sweepings (IR: 40.0%, CR: 16.7%), and the breath-effects (IR: 40.0%, CR: 0.0%). All the five motions had very low CRs, which are in line with the previous results regarding the overall performance of the light patterns in terms of CR. Furthermore, no significant difference of CR was found among the five motions. The median SCs for the conventional blinks and the round-trip sweepings were 4, whereas those for the other motions were 3. The statistical tests reveal that the SC ($p < 0.05$) for the conventional blinks was significantly higher than those for the double fast blinks, the alternating blinks, and the breath-effects.

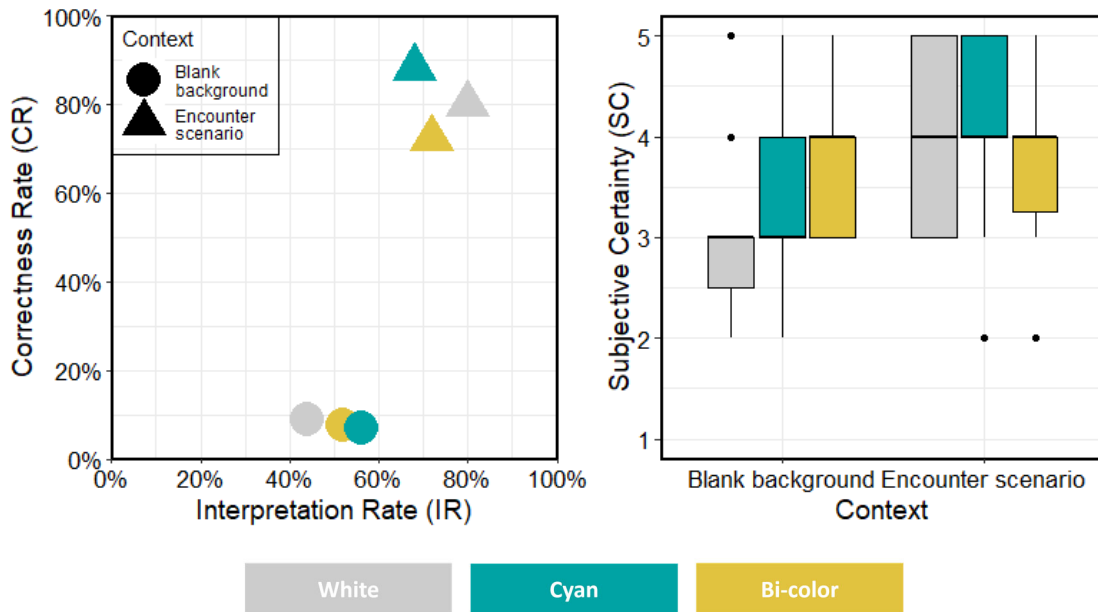


Fig. 3.8 Understandability depending on the color for the light pattern, in terms of the interpretation rate, the correctness rate, and the variation of subjective certainties.

With the encounter scenario, the conventional blinks (IR: 93.3%, CR: 64.3%) always had a higher IR than the other motions. A significant difference of their IR ($p < 0.05$) was found only as compared to the alternating blinks (IR: 46.7%, CR: 100.0%). The CRs increased a lot for all the five motions as compared to the blank background. Still, no significant difference of CR was found among the five motions. The median SC for the round-trip sweepings was 3, whereas those for the four other motions were 4. It is found that the SC ($p < 0.05$) for the round-trip sweepings was significantly lower than those for the conventional blinks, the alternating blinks, and the breath-effects.

Concerning the color, with the blank background, the CRs for the white lights (IR: 44.4% CR: 9.1%), the cyan lights (IR: 56.2%, CR: 7.1%) and the bi-color lights (IR: 52.3%, CR: 7.7%) were very low, which are also in line with the previous results regarding the overall performance of the light patterns in terms of CR. It is found that the differences of IR and CR among the white, cyan, and bi-color lights were not significant. The median SC for the bi-color lights was 4, whereas those for the white lights and the cyan lights were 3. No significant difference of SC was found among them in the statistical tests.

With the encounter scenario, there were big increases of CR for the three colored lights as compared to the blank background. Also, no significant difference of IR and CR was found among them. The median SCs for the three colored lights were all 4, and the significant difference of SC was not found among them.

3.5.3.2 Actor Figure, Action Symbol, Field Figure, and Color for the Pictogram

Fig. 3.9, Fig. 3.10, Fig. 3.11, and Fig. 3.12 associated with Table 3.7 show the understandability

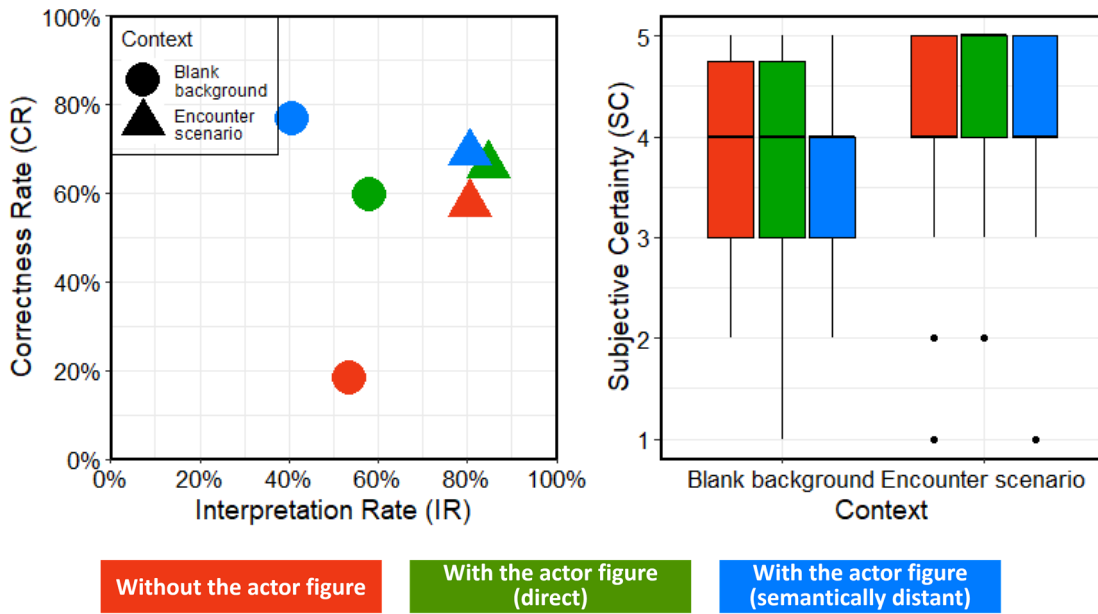


Fig. 3.9 Understandability depending on the existence or absence of actor figure for the pictogram, in terms of the interpretation rate, the correctness rate, and the variation of subjective certainties.

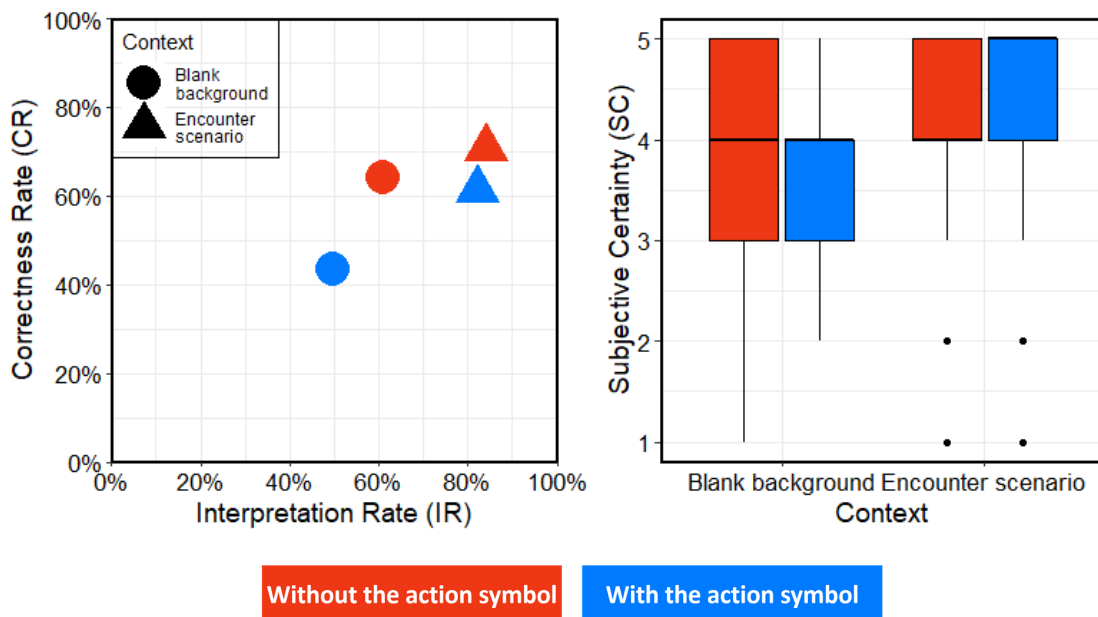


Fig. 3.10 Understandability depending on the existence or absence of action symbol for the pictogram, in terms of the interpretation rate, the correctness rate, and the variation of subjective certainties.

depending on the actor figure, the action symbol, the field figure, and the color for the pictogram.

Concerning the actor figure, with the blank background, each of the pictograms with the direct actor figure (IR: 57.9%, CR: 59.7%) and with the semantically distant actor figure (IR: 40.6%, CR: 76.9%) had a higher CR than the pictograms without the actor figure (IR: 53.7%, CR: 18.2%). The statistical tests reveal that these differences of CR ($p < 0.05$) were significant. Moreover, it is found that the differences of IR among the pictograms with these three levels of

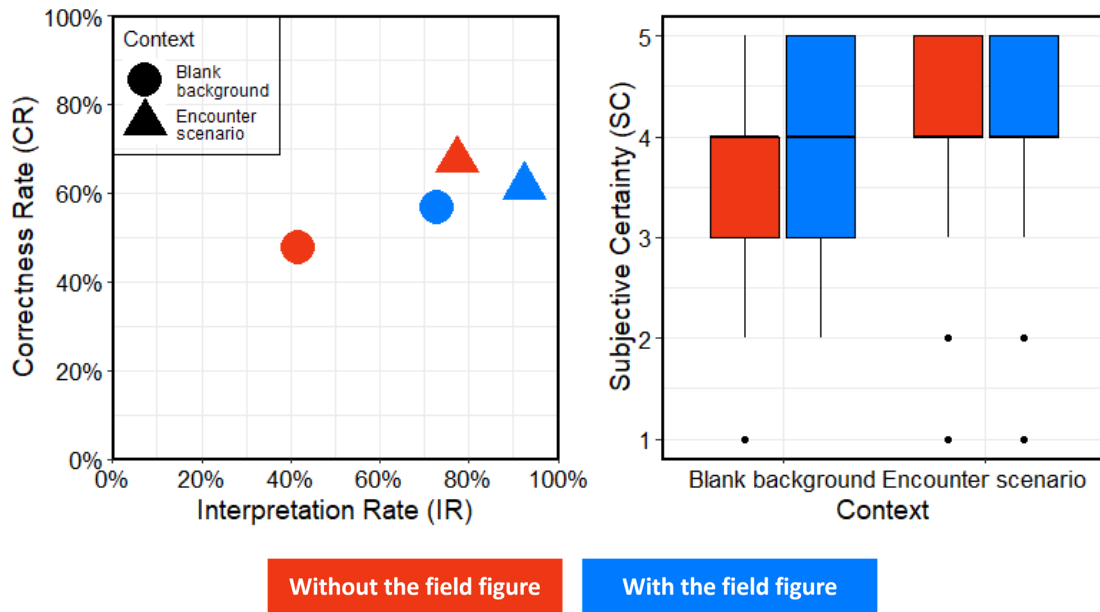


Fig. 3.11 Understandability depending on the existence or absence of field figure for the pictogram, in terms of the interpretation rate, the correctness rate, and the variation of subjective certainties.

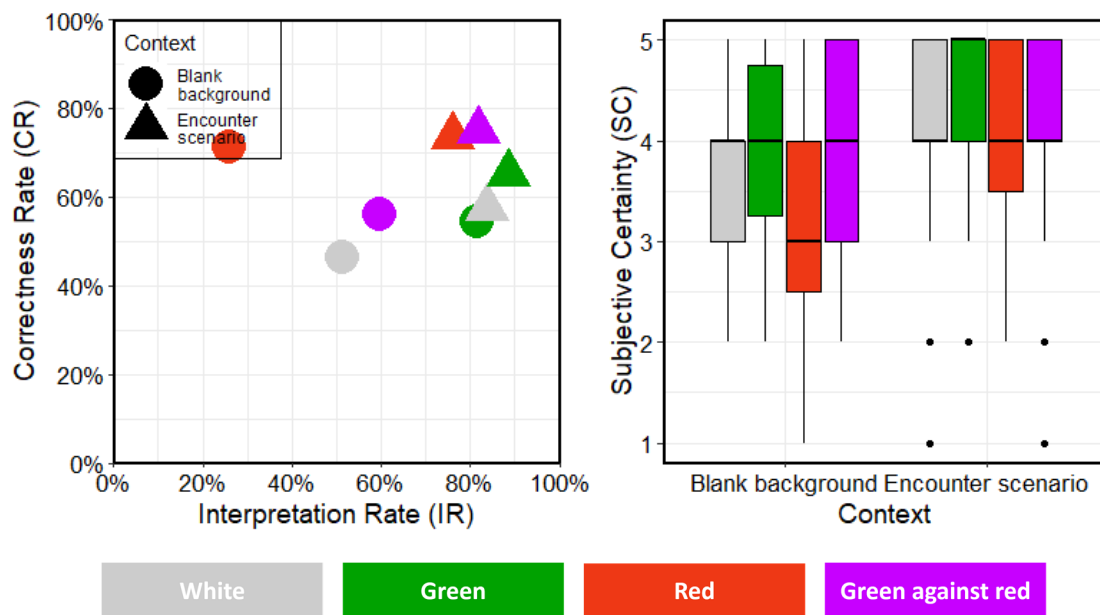


Fig. 3.12 Understandability depending on the color for the pictogram, in terms of the interpretation rate, the correctness rate, and the variation of subjective certainties.

actor figure were not significant. The median SCs for the pictograms with these three levels of actor figure were all 4 and there was no significant difference of SC among them.

With the encounter scenario, the differences of IR and CR among the pictograms with these three levels of actor figure were found to be not significant in the statistical tests. The median SC for the pictograms with the direct actor figure reached 5, whereas those for the pictograms with the semantically distant actor figure and without the actor figure were 4. The significant difference of SC was not found among them.

Concerning the action symbol, it should be pointed out that, with both blank background and encounter scenario, the pictograms with the action symbol actually had lower CRs than the pictograms without the action symbol. Nevertheless, these differences of CR were found to be not significant, as well as the differences of IR. With the blank background, the median SCs for the pictograms with and without the action symbol were all 4. With the encounter scenario, the median SC for the pictograms with the action symbol reached 5, whereas that for the pictograms without the action symbol was 4. Between them, the statistical tests did not find the significant difference of SC with both two contexts.

Concerning the field figure, with both blank background and encounter scenario, the pictograms with the field figure had higher IRs than the pictograms without the field figure. It is further found that their differences of IR ($p < 0.05$) were significant. Besides, it is found that their differences of CR were not significant. The median SCs for the pictograms with and without the field figure were all 4 with both blank background and encounter scenario. No significant difference of SC was found between them in the statistical tests.

Concerning the color, it can be seen that, with the blank background, the pictograms with red color (IR: 25.9%, CR: 71.4%) had the lowest IR. The pictograms with green color (IR: 81.5%, CR: 54.5%) had the highest IR. The pictograms with white color (IR: 51.2%, CR: 46.5%) and opposite colors (IR: 59.5%, CR: 56.0%) had the IRs between the pictograms with red color and with green color. The statistical tests show that the IR ($p < 0.05$) for the pictograms with green color was significantly higher than that for the pictograms with white color. The IR ($p < 0.01$) for the pictograms with red color was found to be significantly lower than that for the pictogram with white color. No significant difference of IR existed between the pictograms with opposite colors and the pictograms with white color. Additionally, it is found that the differences of CR among the pictogram with these four colors were not significant. The median SC for the pictograms with red color was 3, whereas those for the pictograms with the three other colors were 4. No significant difference of SC among these pictograms was found.

With the encounter scenario, it is notable that there was a big increase of IR for the pictograms with red color (IR: 76.0%, CR: 73.7%) as compared to the blank background. The differences of IR and CR among the pictograms with the four colors were found to be not significant. The median SC for the pictograms with green color reached 5, whereas those for the pictograms with the three other colors were 4. The statistical tests did not reveal any significant difference of SC among the pictograms with the four colors.

3.6 Result Analysis and Discussion

3.6.1 Performance of the Light Patterns

In the above results of understandability depending on the signal form and the content type, the extremely low CR for the light patterns with the blank background demonstrates that the light patterns performed badly for correctly expressing the vehicle yielding intention in the condition where no external influence existed. This inherent understandability of the light patterns in aspect of interpretation correctness suggests that they may not be a suitable signal form to convey complex messages for AV2P communication functions. Otherwise, the medium IR and

SC for the light patterns represents that their interpretability and interpretation confidence is ordinary.

Nonetheless, as evidenced by the distribution of the interpretation categories, the light patterns were actually able to convey a warning message. Referring to the existing research work, the similar result was found by A. C. Hensch *et al.* [83] who evaluated three light patterns with the different motions. In their study, the interpretation on the light patterns as a warning message was also observed.

With the vehicle-pedestrian encounter scenario around the crosswalk where the understandability of the light patterns could be influenced by vehicle behaviors, there were increases of IR, CR, and SC as compared to the blank background. Importantly, it should be highlighted that the increase of CR was considerable, which means that the light patterns were much more correctly interpreted. This observation may be explained by the fact that a warning message conveyed by the light patterns evoked a risk awareness towards the vehicle, which led the subjects who played the role of the pedestrian to carefully look out for the vehicle slowing-down and stopping behaviors. Thereby, the subjects associated the meaning of the light patterns with the vehicle yielding intention based on the vehicle movement-based cues [100]. This beneficial effect on evoking a risk awareness seems to be usable for reducing the wrong anticipation on AV behaviors. Still, the reason for this observation can also be that the light patterns left little room for their own interpretation. Because of this, the subjects had to associate their meaning with the yielding intention shown by the explicit vehicle movement-based cues. Taking account of these, it cannot be argued that the light patterns without the help of vehicle behaviors can correctly express the vehicle yielding intention.

In the results of understandability depending on the motion for the light patterns, the statistical tests show no significant difference of CR among the five motions with both blank background and encounter scenario. This finding demonstrates that none of the five motions can comparatively promote nor degrade the interpretation correctness of the light patterns. Besides, the results of IR and SC with the two test contexts presume a trend that, regardless of the interpretation correctness, the conventional blinks were more interpretable and confiding than the other motions. This performance may be linked to the feature of conventional blinks which imitate the regulated automotive hazard light. As it can be met frequently in current traffic and its regulated meaning of warning potential hazards is familiar for road users, more subjects seemed to give such interpretation with a high level of confidence. However, such interpretation of warning potential hazards did not correspond to the yielding intention that we expect the conventional blinks to convey in this study.

As regards the understandability depending on the color for the light pattern, the results of IR, CR, and SC with the two test contexts demonstrate that none of the three colors can comparatively promote nor degrade the interpretability, the interpretation correctness, and the interpretation confidence.

3.6.2 Performance of the Pictograms

In the results of understandability depending on the signal form and the content type, the IRs, CRs, and SCs for the advice, information, and cooperation pictograms indicate that they

performed ordinarily for expressing the vehicle yielding intention with the blank background, and they performed better with the vehicle-pedestrian encounter scenario around the crosswalk. The increases of IR, CR, and SC with the encounter scenario imply that the explicit vehicle behaviors also supported the interpretability, the interpretation correctness, and the interpretation confidence of the pictograms. As regards the differences among the three types of pictograms, it should be pointed out that there was a significantly lower IR for the information pictograms compared to the advice and cooperation pictograms with the blank background. This means that, regardless of the interpretation correctness, fewer subjects were able to give interpretations on the information pictograms in the condition where no external influence existed. This finding may be explained by the lack of prior knowledge and familiarity on the information pictograms. For pictograms which convey egocentric advice or notions of cooperation, they can be frequently met in today's traffic signals, such as traffic lights for pedestrian crossings or traffic signs for indicating the priority over oncoming vehicles. On the contrary, pictograms which convey allocentric information about vehicle maneuvers are rare. Here, compared to the advice and cooperation pictograms, the information pictograms were less interpretable, because the subjects could hardly rely on prior knowledge to realize how to interpret these unfamiliar pictograms. Interestingly, our observations on the pictograms with respect to the different content types is in line with P. Bazilinskyy *et al.* [111] who evaluated the textual signals with respect to the different content types. In their study, a text conveying egocentric advice of "walk" was compared to a text conveying allocentric vehicle information of "will stop". Their results show that "will stop" was more ambiguous than "walk". Otherwise, the results of CR and SC with the two test contexts do not reveal any significant difference of interpretation correctness and interpretation confidence among the advice, information, and cooperation pictograms.

Notably, the diversity of confusion was observed for the pictograms. The main types of confusion were respectively the turning intention, the notification of the crosswalk, and the vehicle awareness of the pedestrian. For the confusion about turning intention, the cause may be linked to the ambiguity of concerned traffic actor. From the identified signal designs involved in this confusion, it is observed that these pictograms contain the action symbol to represent the crossing action but without the actor figure to represent the concerned pedestrian, or with the semantically distant actor figure. Such composing elements seemed incapable of clarifying the concerned pedestrian, so that the action symbol was misinterpreted as the vehicle turning intention. The typical example for supporting this explanation is the advice pictogram N°23 (a white arrow symbol). With the two test contexts, it was largely misinterpreted as the turning intention with high confidence. This confusion about turning intention should be highlighted, as it may probably mislead the decision-making of not only pedestrians but also other drivers. For example, a human driver in the opposite lane, who misinterpreted the pictogram displayed on an AV as the turning intention, may take the wrong driving decision. Traffic conflicts or even dangerous situations may happen due to this confusing signalization. Notably, the confusion about turning intention was not found with the information pictograms, but could take place with some advice and cooperation pictograms.

As regards one other confusion about notification of the crosswalk, it may be due to the similarity to existing traffic signs or the wrong interpretation focus. It is observed that some of the advice pictograms involved in this confusion, for example N°16, 17, 19, 20, are similar to the traffic signs used to inform drivers of the crosswalk ahead. These traffic signs are widely placed around crosswalks in current road systems and its regulated meaning is well-known for

road users. Hence, the subjects might interpret the similar ones as the notification of the crosswalk. Besides, some of the information pictograms involved in this confusion, for example N°29, 30, 31, 32, 33, contain a field figure to represent the crosswalk. Due to the lack of prior knowledge and familiarity on the information pictograms, the subjects seemed to wrongly focus on the field figure, and ignore the actor figure and the action symbol. This led to misinterpretations on the pictograms as the notification of the crosswalk.

Regarding the confusion about vehicle awareness of the pedestrian, the pictograms involved in this confusion all belong to the advice and cooperation pictograms, in which the traffic actor is concerned with the pedestrian. The reason for this confusion may be that the subjects simply interpreted these pictograms as the presence of pedestrians in front of the vehicle without being further aware of any specific vehicle intention.

According to the above performance of the pictograms evidenced by the results, we are still not prepared to draw an argument that someone of the advice, information, and cooperation pictograms is better in terms of understandability. As discussed by P. Bazilinskyy *et al.* [111], the drawback of conveying egocentric advice is that it might be unclear to which pedestrian the message refers. Evidently, this unclearness can be extended to road users other than pedestrians including drivers and two wheels. The observed confusion about turning intention with regard to the advice pictograms which drivers and two wheels could potential have supplements the discussed drawback of conveying egocentric advice. Moreover, regarding the advice of crossing, it may cause pedestrians to ignore potential dangers from other traffics. For example, pedestrians cross the road by following the advice pictograms displayed on an AV, but they do not check the traffic approaching from the opposite lane. Overall, in the case where multiple road users are present in shared road space, the usage of egocentric advice pictograms may be problematic. Being in line with this consideration, there are research works suggesting that an AV should not advise its surrounding road users what to do [160][161] through additional signals but only display its own maneuver [162][163]. These suggestions are consistent with our idea of the information pictograms. The information pictograms do not have the matter about to which road users the message refers, because they are designed for conveying information about the vehicle itself from an allocentric perspective. It is like a message broadcast and other road users can make their decisions accordingly from their own positions. We can observe that all the current automotive signals respect the principle of conveying allocentric information about the vehicle. For instance, the turning signals express that the vehicle itself will turn to the other direction or change the lane. The braking signals express that the vehicle itself will slow down or stop. However, as our results demonstrated, the information pictograms were less interpretable than the advice and cooperation pictograms in the condition where no external influence existed. As compared to the pictograms which convey advice and notions of cooperation, lack of prior knowledge and familiarity with regard to the information pictograms may be the reason. Besides, for the cooperation pictograms, the results demonstrate that their interpretability, interpretation correctness, and interpretation confidence is similar to the advice pictograms. They were more interpretable than the information pictograms in the condition where no external influence existed, but no significant difference of their interpretation correctness and confidence was found as compared to the information pictograms. They are designed by combining the advice pictograms and the information pictograms, so that there will be no matter related to the egocentric or allocentric perspective. However, we did not find in the results that this combination conducted to any distinct superiority.

Concerning the composing elements for the pictogram, the statistical tests about the actor figure show that, with the blank background, the pictograms without the actor figure had a significantly lower CR compared to the pictograms with the direct actor figure and the semantically distant actor figure. These findings demonstrate that, in the condition where no external influence existed, the existence of the direct or semantically distant actor figure benefits the interpretation correctness of the pictograms. The reason can be that the actor figure helps to clarify whether the pedestrian or the vehicle is concerned in the message conveyed.

Compared to the pictograms without the action symbol, there were lower CRs for those with the action symbol with the two test contexts. This indicates that the action symbol tends to degrade the interpretation correctness, though the statistical tests do not reveal it clearly. This may be due to a large number of confusion about turning intention, caused by the pictograms with only the action symbol but without the clear actor figure.

Regarding the noteworthy results of IR for the pictograms with and without the field figure, the statistical tests demonstrate that the existence of field figure eases the interpretability of the pictograms with the two test contexts. The reason can be that the field figure indicates directly that the message conveyed is related to the crosswalk. Such extra information seemed helpful for the subjects to suppose the meaning of the pictograms. However, the results of CR indicate that the existence of field figure does not promote the interpretation correctness of the pictograms. This may be explained by the fact that some of the pictograms with the field figure were misinterpreted as the notification of the crosswalk.

The IRs and CRs for the pictograms with different colors indicate that, with the blank background, the pictograms with green color perform better than those with white color in the aspect of interpretability, but the effect of green color on the interpretation correctness is not obvious. The reason can be that, beyond interpreting the green color as the permission of crossing, the interpretations on the pictograms depends primarily on the actor figure, the action symbol, and the field figure. Despite the green color in the pictograms, the unfitted selection and combination of the figures and the symbol may always lead to confusion. One typical example to support this explanation is the advice pictogram N°20 (a green pedestrian figure with a crosswalk figure). Due to its high similarity to the existing traffic sign used to inform drivers of the crosswalk ahead, the confusion about notification of the crosswalk largely happened. Although the green color exists in the pedestrian figure, it could hardly realize the expected effect on expressing the permission of crossing. Interestingly, this explanation is in line with P. Bazilinskyy *et al.* [111]. In their study on the colored textual signals, it is argued that the color cannot play a dominant role in determining the interpretation on a signal, but acts only as a reinforce. Otherwise, with the blank background, fewer subjects gave interpretations on the pictograms with red color compared to those with white color. However, this was not the case with the encounter scenario. This change reflects that the interpretation on the red color depends on the context. In the context where the vehicle behaviors were shown up, the pictograms with red color were more interpretable.

3.6.3 Comparison between the Light Patterns and the Pictograms

According to the above results and analysis, it is notable that the differences of

understandability between the light patterns and the pictograms were more evident with the blank background where no external influence existed than with the vehicle-pedestrian encounter scenario where the explicit vehicle behaviors supported the understanding of the light patterns and the pictograms. With the blank background which can reveal the inherent understandability, it is notable that the light patterns had an extremely low CR. Meanwhile, their CR was significantly lower than that for each of the three types of pictograms. This demonstrates that the light patterns performed badly for correctly expressing the vehicle yielding intention, whereas the pictograms performed relatively better. Regarding the light patterns, it is further observed that none of the different motions and colors can promote the interpretation correctness. Such performance suggests that one important barrier to use light patterns in AV2P communications lies in how to make pedestrians understand their given meaning, rather than proposing more new designs by differing the motion or the color. For this, a learning phase would be highly required with the help of traffic administration. Regarding the pictograms, their relatively better performance suggests that it would be better to rely on them to convey complex messages in AV2P communications. However, the observed results imply that one potential risk of the pictograms consists of confusion if they were not well designed. The ambiguity of concerned traffic actor, the similarity to existing traffic signs, and the wrong interpretation focus might lead to the misinterpretations on the pictograms as a turning intention or a notification of the crosswalk. Such confusion needs to be overcome in the design process for achieving the correct usage of pictograms in AV2P communications.

3.7 Summary and Recommendations

In this section, we summarize the key findings obtained from the tests on the understandability of the light patterns and the pictograms. Then, based on these findings, we draw some recommendations on the design basis for extended signals used in AV2P communications.

As regards the light patterns proposed to express the vehicle yielding intention:

- Their inherent understandability in the aspects of interpretability and interpretation confidence was ordinary. Their inherent understandability in the aspect of interpretation correctness was unsatisfactory. Nevertheless, they were able to convey a warning message.
- With the support of the explicit vehicle yielding behaviors, their understandability in the aspects of interpretability, interpretation correctness, and interpretation confidence increased to adequate levels.
- It cannot be argued that the light patterns are able to correctly convey the vehicle yielding intention without the support of the explicit vehicle behaviors.
- The conventional blinks tended to have a better interpretability and interpretation confidence. However, they could be misinterpreted as the warning of potential hazards.
- None of the different motions (conventional blink/double fast blink/alternating blinking/round-trip sweeping/breath-effect) and colors (white/cyan/bi-color) can comparatively promote nor degrade the interpretation correctness of the light patterns.

For having well-understandable light patterns used in AV2P communications:

- The efforts in the composing elements by differing the motion and the color are not

recommended, as they cannot contribute to enhancing the understandability.

- Instead of proposing more light patterns by differing the motion and the color, we recommend to rely on external efforts to make pedestrians learn and understand their expected meaning. For instance, standard developing organizations and traffic administrations regulate a light pattern dedicated to AVs which expresses the yielding intentions.

As regards the pictograms proposed to express the vehicle yielding intention:

- Their inherent understandability in the aspects of interpretability, interpretation correctness, and interpretation confidence was ordinary.
- With the support of the explicit vehicle yielding behaviors, their understandability in the aspects of interpretability, interpretation correctness, and interpretation confidence increased to adequate levels.
- The diversity of confusion was observed with regard to the pictograms. The turning intention, the notification of the crosswalk, and the vehicle awareness of the pedestrian could happen due to the ambiguity of concerned road users, the similarity to existing traffic signs, and the wrong interpretation focus.
- As regards the difference among the advice, information, and cooperation pictograms, the information pictograms which are unfamiliar to road users had worse inherent interpretability than each of the advice and the cooperation pictograms. The differences between the advice pictograms and the cooperation pictograms were not significant.
- The egocentric advice pictograms have the drawback that it is unclear to which road user the conveyed message refers. The confusion caused by this drawback may lead to traffic conflicts or even dangerous situations. In the case where multiple road users are present in shared road space, the usage of egocentric advice pictograms may be problematic. However, this is not the case for the allocentric information pictograms and the cooperation pictograms.
- Inherently, each of the advice, information, and cooperation pictograms had better interpretation correctness than the light patterns.
- The existence of actor figure benefits the interpretation correctness of the pictograms, as it contributes to clarifying whether the vehicle or the pedestrian is concerned in the message conveyed.
- The single usage of action symbol in the pictograms without the clear actor figure was bad for the interpretation correctness, as the ambiguity of concerned road users could cause confusion.
- The existence of field figure eases the interpretability of the pictograms, as it provides extra information about the concerned traffic field which is helpful for supposing the meaning of the pictograms. However, in the case where the wrong interpretation focus happened to the field figure, confusion could take place.
- The pictograms with green color performed better in the aspect of interpretability. However, the green color did not contribute significantly to the interpretation correctness. The reason can be that the interpretation on the pictograms depends primarily on the actor figure, the action symbol, and the field figure. The color only acts as a reinforce in the interpretation on the pictograms.

For designing well-understandable pictograms used in AV2P communications:

- We personally recommend to rely on the information pictograms and the cooperation pictograms to convey AV intentions instead of the advice pictograms. Even though the allocentric information pictograms were inherently less interpretable, it can be supposed that pedestrians are used to taking conservative behaviors when they are not able to interpret pictograms displayed on the vehicle in traffic. Such behaviors ensure safety to a certain extent. For the egocentric advice pictograms, the confusion caused by referring to wrong road users could be more dangerous than a non-interpretation in the aspect of road safety. For the cooperation pictograms, their understandability is found to be similar to the advice pictograms. As they are designed by combining the advice pictograms and the information pictograms, there will be no matter related to the egocentric or allocentric perspective.
- The actor figure is highly recommended to be added into the pictograms in order to ensure that the concerned road user is clear in the message conveyed.
- The usage of action symbol should be cautious. The action symbol is normally abstract, so that a single action symbol in a pictogram may be confusing with regard to the concerned road user. The usage of action symbol accompanied with the actor figure is highly recommended.
- The field figure is recommended to be added into the pictograms for providing extra information about the concerned traffic field. However, the field figure should not be designed in a particularly conspicuous way in order to avoid the wrong interpretation focus. The simplification or size reduction of field figure can be applied to do so.
- For the design order related to the figure, the symbol, and the color in the pictograms, the selection and combination of figures and symbols should be put in the first place for ensuring basic understandability. After that, the color can be added for subsequently enhancing the understandability.
- Figures and symbols which are familiar to road users are recommended to be used in the pictograms for easing the understanding. However, it should be pointed out that familiarity is not equal to similarity. The similarity to existing traffic signs can cause confusion, which should be prevented in the design of pictograms.

3.8 Limitations

Even though the results gathered in this study allowed us to draw the first conclusion on the understandability of the signals in the forms of light patterns and pictograms, the limitations still exist. One limitation concerns the influences of individual differences, including culture, age, driving experience, on the understanding of the signals, which were not investigated in this study. The related research works have revealed that people with different cultures, adults, children might have different reactions when facing new signals used in AV2P communications [111][121][186]. It cannot be ignored that these individual differences could lead people to understand the signals in different ways. This study should be further completed by integrating these influencing factors in the result analysis and trying to clarify their possible effects.

There is another limitation related to the expectation of right of way, which was not controlled in the tests with the vehicle-pedestrian encounter scenario including a crosswalk [187][188]. For the subjects who played the role of the pedestrian, the presence of a crosswalk in the environment would suggest that the vehicle has to give the right of way to them, as yielding to

pedestrians when they are next to the crosswalk and are about to cross the road is regulated in many countries such as France and Germany. It is possible that the subjects interpreted the tested signals as the yielding intention under the influence of such expected right of way suggested by the crosswalk. This reflects that the expectation of right of way might support the subjects to understand the tested signals. In order to identify this effect of expectation on the understanding of the signals, the tests with the encounter scenario should be further extended by adding an opposite condition where the vehicle does not yield to the pedestrian around the crosswalk.

3.9 Conclusion

The future road space shared with AV calls for safe and efficient interactions between this new road user and its surroundings, especially pedestrians who are vulnerable in traffic. To fulfill this requirement, AV2P communication functions which express AV intentions through extended signals are expected to contribute to constituting smart cooperation between AVs and pedestrians. Without the frames shaped by formal standards in the early stage, academics and industries designed numerous new signals with great liberty. For these signals, it is observed that some of them did not achieve the desired effects on leading to safe and efficient pedestrian behaviors [83][84]. The cause is probably that the related signals were improperly designed. In consequence, they performed ineffectively for communicating AV intentions to pedestrians. This question suggests that the rational design basis for new signals and the effective evaluation on the performance of extended signals are lacking heavily. As regards the design basis, the new signals used for AV2P communication functions were principally designed in four most discussed forms involving light patterns, pictograms, texts, and anthropomorphism. Yet, no common consensus has been made on how to deal with their elemental composition for appropriate signal designs. As regards the performance, the adopted signals must be understandable for being able to provide the effective AV2P communications. However, the understandability, as a key factor to evaluate the performance of extended signals and select the most promising ones, has been less studied. Facing these lacks, we attempted to evaluate the understandability of extended signals in the different forms and summarizing the usable guidelines for the signal design. In this study, we were particularly interested of whether light patterns and pictograms can handle the job of understandably expressing the vehicle yielding intention. We proposed the conventional blink, the double fast blink, the alternating blinking, the round-trip sweeping, and the breath-effect as the motions for the light patterns. Meanwhile, we proposed the white and the cyan, as the colors for the light patterns. Creatively, we tried a bi-color configuration where the white light with the motions and the static cyan light are grouped, as another possible color for the light patterns. Otherwise, for the pictograms used to express the vehicle yielding intention, we proposed a group of advice pictograms which convey an advice message of crossing from an egocentric perspective taken by the pedestrian, a group of information pictograms which convey information of vehicle stopping from an allocentric perspective, and a group of cooperation pictograms which convey a notion of cooperation by combining the advice and information pictograms. Importantly, these signals were designed in a controlled manner with the purpose of carrying out a comparative analysis on the understandability depending on the signal form (light pattern, pictogram), the content type (egocentric advice, allocentric vehicle information, notion of cooperation for the pictogram),

and the composing elements (motion and color for the light pattern, figure, symbol and color for the pictogram). In order to evaluate efficiently the understandability of our proposed signal designs, we decided to carry out monitor-based tests with the help of an online test interface. In the online test interface, the usage of signal designs in AV2P communications with the blank background and with the vehicle-pedestrian encounter scenario around the crosswalk were demonstrated in the form of the animated scene to the subjects. Meanwhile, the subjects' responses to the signal meaning were recorded by compact surveys. According to the recorded responses, four indicators, including the interpretation rate, the correctness rate, the variation of subjective certainties, and the distribution of interpretation categories were calculated to represent the understandability of the signal designs in the aspects of interpretability, interpretation correctness, interpretation confidence and confusion. Based on our method and tests, the representative results on the difference between the light patterns and the pictograms were found in the tests with the blank background which can reveal the inherent understandability. For the light patterns, it is found that they performed badly for correctly expressing the vehicle yielding intention. Besides, none of the proposed motions and colors can promote the interpretation correctness of the light patterns. Such performance of the light patterns implies that they may not be a suitable signal form for conveying complex messages in AV2P communications. For the pictograms, their performance in terms of understandability was relatively better. Still, we must point out that some of them which were not well designed could cause the different types of confusion. Additionally, it is found that the actor figure and the field figure could ease the understanding of the pictograms. As regards the difference among the advice, information, and cooperation pictograms, we cannot argue yet that someone of them is better in AV2P communications by considering the matter related to the egocentric or allocentric perspective. Regarding the limitations, our study should be further completed by considering the effects of individual differences, including culture, age, and driving experience, and expectation of right of way on the understandability. Overall, the main contribution of this study is that it sheds new lights on the understandability of light patterns and pictograms in a precise way. To our knowledge, this is the first trial in this domain which summarizes systematically as what exactly pedestrians understand the extended signals involving the correct interpretation and, most importantly, the different types of confusion. In addition, this study analyzed the understandability of light patterns and pictograms from the perspective of their composing elements, based on which the recommendations on the design basis were drawn. The results gathered in this study provide more evidence for the comparisons between light patterns and pictograms, which can be useful for selecting the appropriate signal designs in AV2P communications. Certainly, the comparison between light patterns and pictograms should take account of other aspects. As advised by the responsible of our industrial partner, Dr. Gonçalves Whilk, from Stellantis company, another important aspect to compare light patterns and pictograms is the impact on automotive engineering. On the one hand, the usage of new light patterns by integrating them into turn indicators or day running lights can make these classic organs of automotive signalization system become polyvalent and multifunctional, which will not bring a huge impact to the current vehicle architecture. On the other hand, the usage of pictograms in a vehicle requires a huge surface to install high-resolution display devices for ensuring the visibility of pictograms from a long distance. Besides, since pictograms are relatively complex in their form, they would probably cause uncomfortable visual pollution and disturbance in urban areas. The placement and dimension of pictograms on AVs are the main obstacles for engineering.

Chapter 4. Observing and Quantifying the Vehicle-Pedestrian Interaction: Towards Pedestrian-Adapted AV2P Communication Functions Through Extended Signals

4.1 Context and Purpose

For having effective AV2P communication functions, the extended signals used to express AV intentions must be understandable with respect to pedestrians. This can be considered as one vital foundation for the adoption of this technological solution. In addition to validating the understandability, the employment strategy of extended signals should also be taken into account for allowing AV2P communication functions to be successfully implemented in future traffic interactions. This assumption is conducted by our observation on the failure of some AV2P communication functions. In the field experiments of M. Clamann *et al.* [28] which assess the functionality of an intention communication interface, it is observed that the demonstrated extended signals were not regarded as a reliable source for pedestrians to make their crossing decision. The study of D. Dey *et al.* [84] shows that pedestrians fall back to movement-based cues, e.g. the vehicle speed and distance from the vehicle to the pedestrian, to decide whether to cross the road, rather than relying on extended signals. The investigation of Y.B. Eisma *et al.* [137] reveals that the signals projected on the road used to express the AV intention were distracting for pedestrians to focus on the vehicle state. Based on our analysis, these abandonments of relying on extended signals may be linked to the fact that their employment strategies in terms of activation timing and placing position did not respond to pedestrians' communication habits. In day-to-day vehicle-pedestrian interactions, pedestrians apply some communication habits to look for information from surrounding environments, such as looking for the vehicle speed variation or gazing at the face of a human driver. Getting useful information in time and in place is essential for pedestrians to make the decisions [54][100][127]. Even though AV2P communication functions provide through extended signals a new and powerful information source of AV status and intentions, a retard or a wrong place of their employment may always disturb pedestrians to get information in an expected way. Consequently, pedestrians had to abandon the extended signals and fall back to the basic vehicle-pedestrian communications which they are used to [100][104][127][129][130]. This represents one essential question of developing AV2P communication functions, which is when to activate and where to place the extended signals. Since pedestrians highly rely on the basic communications through implicit and behavioral channels to interact with manually driven vehicles in today's traffic and no evidence has proven that pedestrians will no longer rely on them to interact with AVs in the future, it seems preferable to take account of these basic communications in the development of AV2P communication functions. Therefore, in order to better understand the basic communications between vehicles and pedestrians, and recognize the suitable way to employ extended signals, it would be helpful to take close observations on today's vehicle-pedestrian interactions with particular attention to how the information was communicated between vehicles and pedestrians. This chapter aims at studying this question

and intends to recommend a pedestrian-adapted employment strategy of extended signals for AV2P communication functions.

4.2 Scope of the Present Study

The “interaction” can be defined as a situation where the behaviors of at least two road users can be interpreted as being influenced by the possibility that they are both intending to occupy the same space at the same in the near future [164]. So far, a large number of research works have been made on the topic of vehicle-pedestrian interaction for studying the way in which vehicles and pedestrians behave, the factors impacting the decision-making, and the communications occurred between pedestrians and vehicles [35][36]. For instance, it is found that the vehicle speed variation often work as an implicit indicator of the vehicle intention in today’s vehicle-pedestrian interactions [54][104]. Pedestrians are used to carrying out the gaze behavior towards vehicles to seek useful information for making crossing decisions [100][127]. Many factors, involving road conditions, demographics, culture, and social elements, can influence the vehicle and pedestrian decision-making in their interactions [165]-[168]. Despite the rich research on the vehicle-pedestrian interaction, nothing prevents us from observing again vehicle-pedestrian interactions and giving our own analysis on them. Hence, facing a big variety of traffic situations in shared road space, we intentionally selected to observe the vehicle-pedestrian interaction around the unsignalized urban crosswalk as our first step to exploring the suitable way of employing extended signals. By observing this typical interaction case which can be frequently met on today’s and future road, our special task is to search for useful hints that can inspire us to give reasonable recommendations on when to activate and where to place new extended signals for adapting to pedestrians.

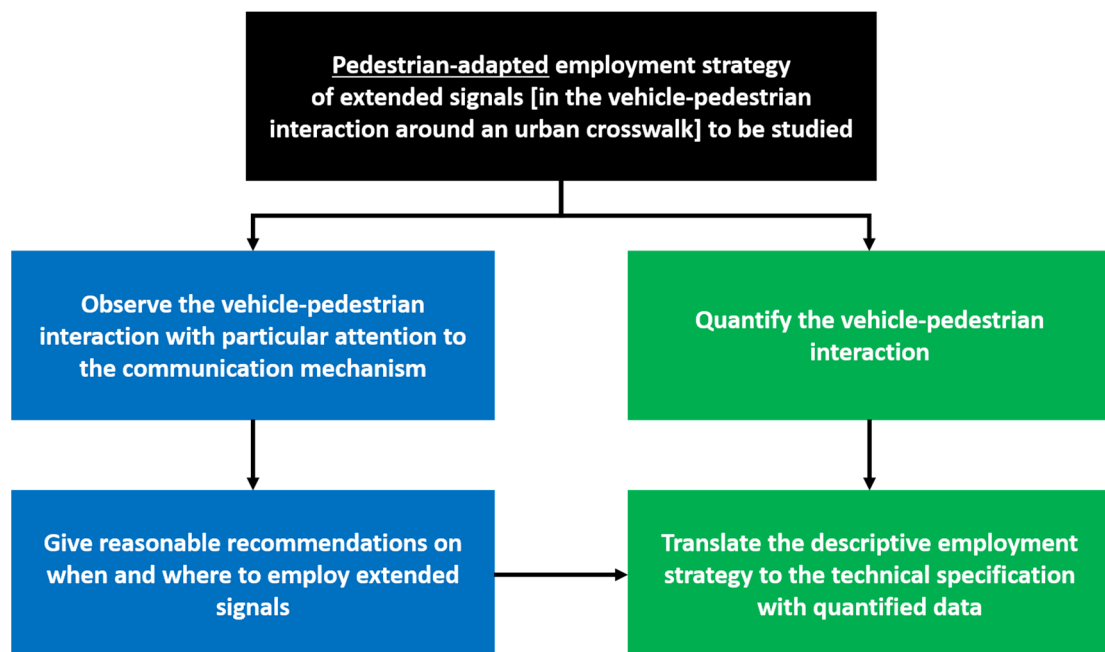


Fig. 4.1 Scope of the present study: observe and quantify the vehicle-pedestrian interaction for the pedestrian-adapted employment strategy of extended signals.

In the existing research works on vehicle-pedestrian interactions, some interesting suggestions have already been made for responding to when to activate and where to place extended signals. Regarding the activation timing of extended signals, the helpful insights can refer to D. Dey *et al.* [84] who recommend that the alignment between explicit communication (communication interface) and implicit communication (movement-dynamics and kinematics) facilitate the most effective communication of AV yielding intentions. In the use case where the extended signals are designed for expressing the AV yielding intention, this recommendation can be explained as the extended light signal should be activated when the vehicle decelerates the speed. It makes sense as both extended light signal and vehicle speed variation act as the indicator of vehicle yielding intention. Furthermore, we argue that the principle of alignment should also include the pedestrian gaze behavior in order to respond to this pedestrians' habit. As pedestrians employ gaze behaviors to look for useful information about the vehicle intention [100][127], it is like a sensor which detects the vehicle intention aims at its target which represents the vehicle intention. However, this supposition should be further confirmed by close observations on the vehicle speed and the pedestrian gaze behavior. For the placing position of extended signals, Y.B. Eisma *et al.* [137] recommended several options including the vehicle bumper, radiator grille, windshield, and roof, based on their research on the fixation pattern of pedestrian gaze behavior. Still, these options seem to be too wide to specify the most promising placing position of extended signals. It would require more studies on the pedestrian gaze behavior. Considering these recommendations and their potential shortages, our study was particularly interested in the significant vehicle and pedestrian behaviors which contribute to constituting a communication of vehicle status and intention in the vehicle-pedestrian interaction.

A suitable employment strategy in terms of when and where to employ extended signals is crucial for the functionality of AV2P communication functions in future traffic interactions. Ideally, this employment strategy should be further translated to a technical specification instead of remaining only as a descriptive principle. Thereby, automotive engineers can depend on it to develop functional extended signalization systems equipped on AVs. This would require the proposed employment strategy to be presented with quantified data. As mentioned previously, a large number of research works have addressed the behaviors, the influencing factors, and the communications in vehicle-pedestrian interactions. Their underlying reason-effects were widely explained and discussed. However, it seems there is a missing effort on quantifying the vehicle-pedestrian interaction. This study direction may open a new perspective to view and understand the vehicle-pedestrian interaction. Hence, our study includes a specific quantitation of the vehicle-pedestrian interaction, which is expected to help to propose suitable employment strategies with quantified data (see Fig. 4.1).

4.3 Method

4.3.1 Naturalist Field Observation with Video Recording

To study how pedestrians interact with vehicles, the field observation is a direct method to take note of what happens in the vehicle-pedestrian interaction. For field observations, they can be both naturalistic and scripted. In a naturalistic field observation, pedestrian and vehicle behaviors are monitored by researchers without notifying them of the ongoing observation

[169]. In a scripted field observation, a part of road users is instructed to behave in a defined way and the reaction of the other naïve road users are monitored [75][136]. However, it should be underlined that this method may contain potential biases, which are due to researchers' subjective judgment and misinterpretation on observed road users' behaviors. Furthermore, field observations supported with instruments like sensors and cameras gained great popularity in recent years. The naturalistic video recording of traffic scenes is perhaps one of the most effective methods for studying traffic [36]. In this updated field observation, a camera or a group of cameras is applied to record and save permanently the traffic scenes [54][59][125]. Subsequently, more researchers can review the recorded traffic scenes with more time and in detail, which allows to acquire a better understanding of the underlying motives lying behind the studied traffic activities. This can be a beneficial way to reduce the potential bias caused by researchers' subjective misinterpretation. Additionally, the field observation can be completed with surveys and interviews, which are generally used in the case where the measurement of individual differences or attitudes on the studied traffic activity is needed [27][49][50]. Normally, the surveys and the interviews with prepared questions are launched after road users have experienced the studied traffic activity in order to collect the required information. However, these two tools supplemented in the field observation are often criticized for raising biases caused by responders' honesty and bad recall of the traffic activity. Besides, with the development of numerical simulation in recent years, VR becomes a practical method to observe the interaction among road users [124][170] in a laboratory setting. Being immersed in a virtual traffic scene in which surrounding road users act in a scripted way, test participants with the defined traffic task are required to make certain reactions. Participants need to manipulate the controller in hand for allowing the measurement of their reactions. Still, some oppositions argue that VR cannot reproduce real traffic scenes, whose results may not be able to completely represent road users' true behaviors in vehicle-pedestrian interactions. Additionally, accident reports provided by transportation departments are one possible source to observe vehicle-pedestrian interactions in an indirect way [171]. The advantage of these documents is that they provide good details regarding the positions of personnel involved in accidents. However, what is not enough is that only the interactions in traffic accidents can be studied.

In this study, the naturalistic field observation supported by video recording was selected for observing the vehicle-pedestrian interaction on account of its flexibility and reviewability. Starting by observing and recording traffic scenes in two selected unsignalized urban crosswalks, we gathered the video clips which contain both the vehicle and the pedestrian around the unsignalized crosswalk at the same time. These videos are considered as the vehicle-pedestrian interaction samples for the further review and quantification. Based on these samples, we reviewed and took note of what happened exactly in the vehicle-pedestrian interaction in order to recognize vehicle and pedestrian behaviors. In the next, the quantification with respect to the vehicle-pedestrian interaction samples was carried out for analyzing the vehicle and pedestrian behavioral patterns in terms of V2P distance and V2P angle.

4.3.2 Observation Site and Extent

The vehicle-pedestrian interaction around the unsignalized urban crosswalk where a pedestrian

intends to cross the road and encounters an approaching vehicle represents a typical traffic case that can be frequently met. Focusing on this case, our naturalistic field observation was carried out on two sites which have the same road structure:

- two lanes bidirectional road;
- speed limit of 30 km/h;
- crosswalk marking on the road;
- without traffic signal lights.

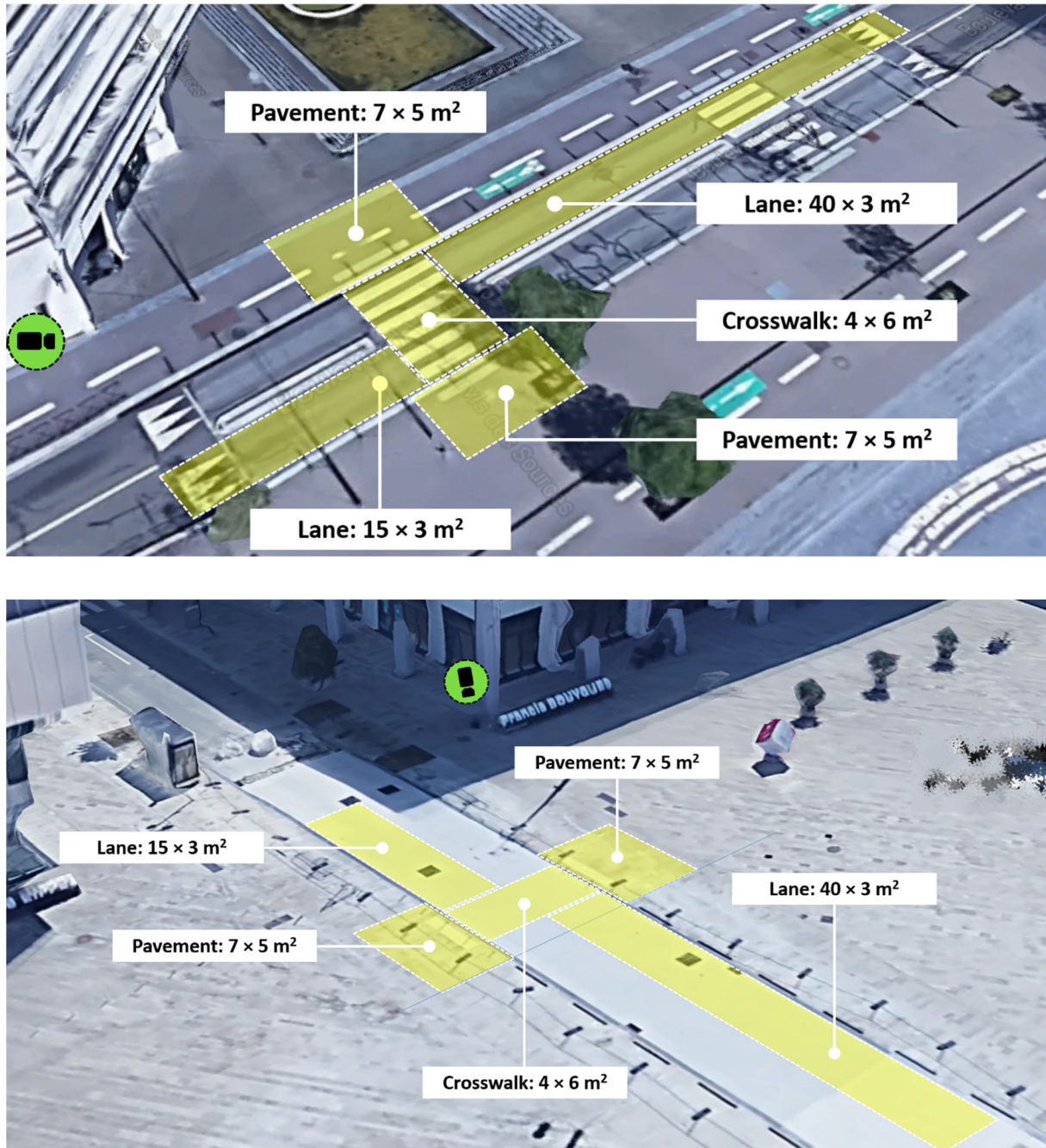


Fig. 4.2 Overview of the two selected observation sites (observation extent in transparent yellow) and the camera setup.

One observation site is located inside a scholar campus and the other one is located in the vicinity of a commercial center in Paris, France (see Fig. 4.2). In these two sites, a large number of local students and residents cross the road frequently and have to interact with approaching vehicles. To prepare the field observation, a camera was hidden inside a carton box on the pavement in order to have a video recording which does not disturb the natural vehicle and pedestrian behaviors. Besides, the camera was not installed in a much close proximity to the crosswalk in order to have a wide view angle. This installation can also avoid recording a lot of appearances of road users for securing the anonymity. Considering that the important behaviors that contribute to a communication of vehicle status and intention generally take place in the close distance vehicle-pedestrian interaction [54]-[56][127][134][135], we defined an observation extent which is not extremely large and closely attached to the crosswalk. In the two selected sites, the observation extent is set as a zone ($40 \times 3 \text{ m}^2$) on the road lane in the forward direction to the camera, a zone ($15 \times 3 \text{ m}^2$) on the road lane in the opposite direction to the camera, the whole crosswalk ($4 \times 6 \text{ m}^2$), as well as two zones on the pavement close to the crosswalk ($7 \times 5 \text{ m}^2$). Eventually, the naturalistic field observation supported with the video recording was conducted in the two selected sites for 3 hours per day for 3 weeks (15-19/July, 12-16/August, 19-23/August) in 2019.

4.3.3 Vehicle-Pedestrian Interaction Sample

The naturalistic recording carried out in the observation sites provided many hours of video footages in which pedestrian crossing scenes are contained. Evidently, the single performance of pedestrians is not sufficient, as this study tried to observe vehicle-pedestrian interactions with particular attention to how the information is communicated between pedestrians and the vehicle. For the definition of vehicle-pedestrian interaction, it can be outlined as an elementary activity in traffic, when vehicles and pedestrians meet at a given location at the same time [164]. They behave in response to each other, like “a couple coordinating their movements across the dance floor” [172]. Therefore, we split the video footage into short clips and gathered those in which both the vehicle and the pedestrian are presented at the same time within the defined observation extent. These video clips were considered as the vehicle-pedestrian interaction samples (see Fig. 4.3).

4.3.4 Review of the Vehicle-Pedestrian Interaction

The reviews based on the vehicle-pedestrian interaction samples observed and took note of what happened throughout the whole process of vehicle-pedestrian interaction around the crosswalk. This work aims at providing available materials about the observation on vehicle-pedestrian interactions for the further analysis. In the review of each interaction sample, we focused on recognizing the pedestrian and vehicle behaviors in connection with the road-crossing task and searching for the cues on how information is communicated between the vehicle and the pedestrian. The items included in the provided materials covered the following observations: different types of the behaviors (e.g. pedestrian waits at the curb, vehicle slows down), occurrence frequency of the behaviors (once/twice), occurrence order of the behaviors

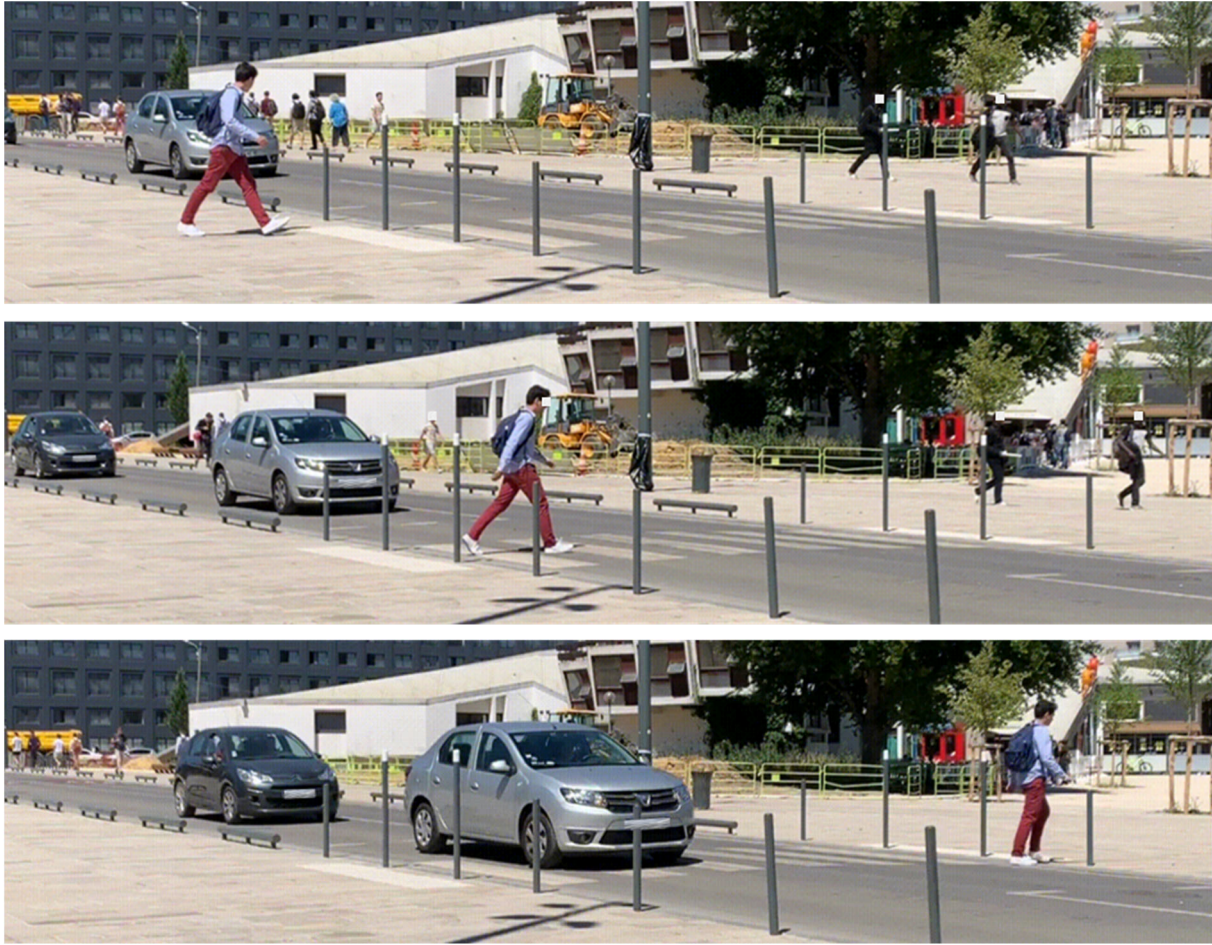


Fig. 4.3 Vehicle-pedestrian interaction sample in the form of video clip in which both the vehicle and the pedestrian were presented at the same time with the defined observation extent.

(e.g. pedestrian crosses the road prior to the arrival of vehicle), estimated distance from the vehicle to the pedestrian (far/close), special situations (e.g. distracted road user, ambiguity, conflict, accident). For the different types of behaviors recognized in the interaction samples, the unique labels were assigned to them and the related video frames were captured. Particularly regarding the behaviors with the occurrence frequency being higher than once, they were further distinguished with respect to the prefixes (i.e. primary, secondary). The occurrence order of the recognized behaviors was noted in the form of a multi-step sequence with the purpose of distinguishing every possible scenario of vehicle-pedestrian interaction around the crosswalk. Regarding the distances between the vehicle and the pedestrian, we made in this review phase the estimation based on the captured video frames containing the behaviors to be studied.

To analyze the materials provided by the review of interaction samples, we used a qualitative approach which open an accessible window to understand human cognition in traffic [173][174]. Essentially, the qualitative approach means to suggest and assume interpretations on the observed things rather than attempt to make the prediction [54]. In this study, the analysis by the qualitative approach focuses on motives, habitudes, and expectations which lie behind the observed behaviors and communications between the vehicle and the pedestrian. To do so, one researcher in our research team firstly tried to interpret the observations. Then, the interpretations were presented to other researchers. If disagreement appeared, other researchers

raised the questionable terms and suggested their interpretations. All researchers compared and discussed the suggested interpretations until the consistency is achieved.

4.3.5 Quantification of the Vehicle-Pedestrian Interaction

Generally speaking, the “interaction” stands for a situation where the behaviors of at least two road users can be interpreted as being influenced by the possibility that they are both intending to occupy the same space at the same in the near future [164]. In a more specific scope, it can be further interpreted as the spatio-temporal relationship between road users, which has the underlying objective to avoid collisions, reduce anxiety, and ensure traffic flow [20]. By combining these comprehensions on the “interaction”, we proposed a perspective that the vehicle-pedestrian interaction can be quantified as the position of the pedestrian relative to the vehicle at the time of vehicle or pedestrian behaviors, in terms of the V2P distance and V2P angle (see Fig. 4.4). This perspective involves at the same time the notion of behavior and the notion of spatio-temporal relationship which are both essential for characterizing the interaction among road users. With this perspective, the vehicle-pedestrian interaction can be illustrated and analyzed in a quantitative approach. Taking an example of vehicle behavior, the position of the pedestrian relative to the vehicle at the time of vehicle slowing-down in terms of V2P distance and V2P angle can be calculated by:

$$V2P \text{ distance} = \sqrt{(X_v - X_p)^2 + (Y_v - Y_p)^2}$$

$$|V2P \text{ angle}| = \left| \arctan\left(\frac{X_v - X_p}{Y_v - Y_p}\right) \right|$$

Where

- X_v , Y_v and X_p , Y_p are positional coordinates of the pedestrian and the vehicle in the observation extent.

With the purpose of calculating the V2P distance and V2P angle, the positional coordinates of the vehicle and the pedestrian in the observation extent are required. To extract these coordinates from the interaction samples, we relied on a comparison procedure whose principle is to compare the vehicle and pedestrian position at the time of the behavior to be studied to the most adjacent road markings or reference objects in the related video frames [175][176]. As the real-world dimensions of the road markings and the reference objects, as well as their distances to the supposed original coordinate (intersection between the pavement curb and the crosswalk marking) were measured in the preparation for the field observation, the vehicle and pedestrian coordinate extracted in the video frame scale can be converted to those in the real-world scale. In addition, based on the vehicle coordinates extracted at several time points with the same interval, the vehicle speed variation can be calculated for knowing whether the vehicle is slowing down or driving constantly.

With regard to the vehicle-pedestrian interaction sample, the position of the pedestrian relative to the vehicle at the time of vehicle or pedestrian behaviors in terms of V2P distance and V2P

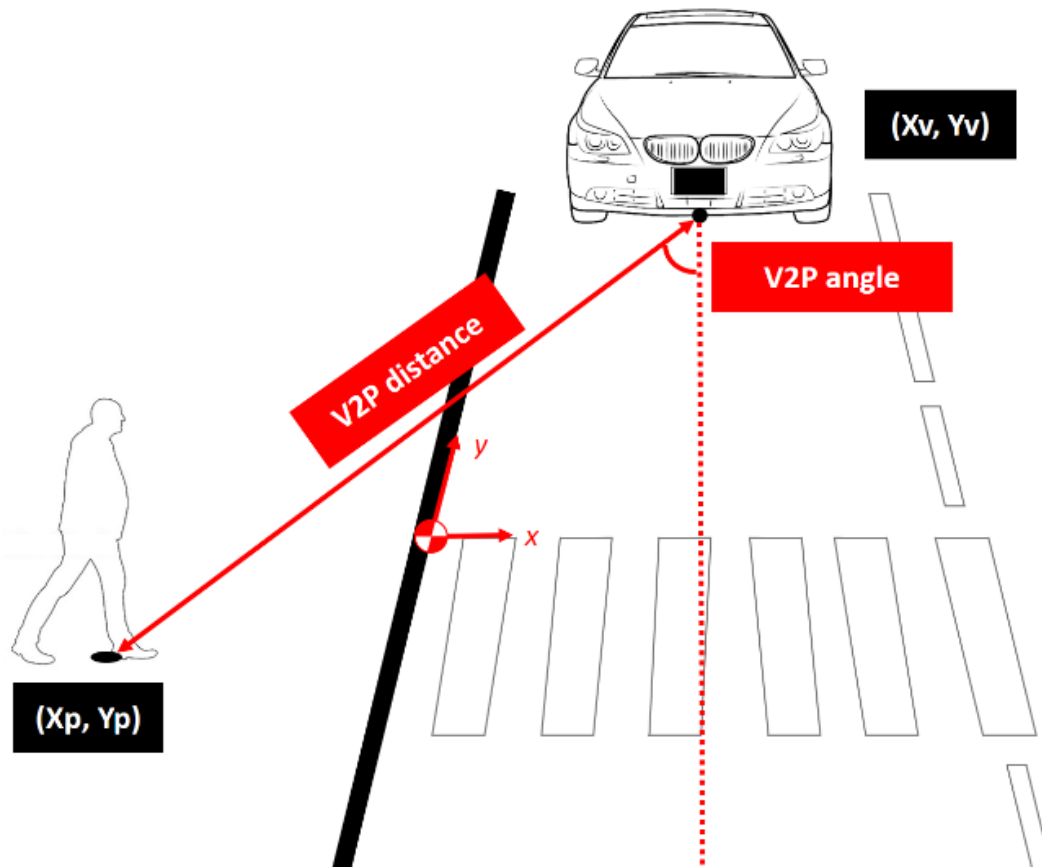


Fig. 4.4 Position of the pedestrian relative to the vehicle at the time of vehicle or pedestrian behaviors, in terms of the V2P distance and V2P angle.

angle consists of a measure to reveal where vehicle and pedestrian behaviors take place in their interactions and what are their behavioral patterns. To illustrate these positions, we relied on the distribution and the probability density of vehicle and pedestrian behaviors as a function of V2P distance and V2P angle. The usage of these statistical tools would be more efficient in recognizing and predicting vehicle and pedestrian behavioral patterns.

4.4 Results of Observing the Vehicle-Pedestrian Interaction

As a result, the naturalistic field observation recorded approximately 26 hours of traffic scenes around the two urban crosswalks. A total of 952 pedestrians were observed and included in the recorded video footage. The footage was split into 529 short video clips in which pedestrian crossing scenes are involved. Amongst them, there are 342 video clips in which pedestrians realized the crossing task without meeting any approaching vehicles and 187 video clips in which pedestrians interact with vehicles in the observation extent. Since this study aims at observing vehicle-pedestrian interactions, the above 187 video clips were considered as the vehicle-pedestrian interaction samples and taken into account for the further review and quantification.

4.4.1 Vehicle and Pedestrian Behaviors

By reviewing the vehicle-pedestrian interaction samples, 8 typical vehicle and pedestrian behaviors were recognized and labeled respectively:

- Pedestrian walking
- Pedestrian gaze
- Pedestrian waiting
- Pedestrian crossing
- Vehicle approaching
- Vehicle keeping-driving
- Vehicle slowing-down
- Vehicle stopping

On one side, *Pedestrian walking* represents an observed behavior that the pedestrian initially walks towards the crosswalk in the vehicle-pedestrian interaction (see Fig. 4.5). *Pedestrian gaze* is a behavior that the pedestrian looks intently towards the approaching vehicle. For the recognition of this behavior, the pedestrian's head orientation is an obvious indication. *Pedestrian waiting* means a behavior that the pedestrian rests standstill at the curb next to the crosswalk. Relatively, *Pedestrian crossing* indicates a behavior that the pedestrian departs from the curb and passes longitudinally through the crosswalk. On the other side, *vehicle approaching* is an observed behavior that the vehicle approaches towards the crosswalk in the vehicle-pedestrian interaction. *Vehicle keeping-driving* represents that the vehicle maintains or accelerates the speed to pass transversely through the crosswalk. *Vehicle slowing-down* indicates that the vehicle decelerates the speed to yield to the pedestrian. *Vehicle stopping* means that the vehicle decelerates until a complete stop before the crosswalk to yield to the pedestrian.

Particularly regarding the pedestrian gaze, this visual behavior, which seems to happen in a spontaneous way, was observed in nearly all the vehicle-pedestrian interaction samples (176/187 samples). Compared to the other pedestrian behaviors, it is found that the pedestrians could gaze towards the vehicle during their walking, waiting, or crossing. Furthermore, within the defined observation extent, we noticed that the pedestrian gaze occurred once or twice in the vehicle-pedestrian interaction (see Table 4.1). In the samples with once gaze (see Fig. 4.6c), it generally took place when the distance between the vehicle and the pedestrian was close (102/187 samples). In the samples with twice gazes (see Fig. 4.6b and d), a primary gaze often took place when the approaching vehicle was far from the pedestrian and a secondary gaze happened when the vehicle came closer (74/187 samples). Nevertheless, the exceptional samples existed in our observations in which the pedestrians were distracted by the mobile phone and displayed attentional blindness while encountering the approaching vehicles (11/187 samples). The pedestrians involved are observed to have no awareness of the approaching vehicles (see Fig. 4.6a).

Table 4.1 Occurrence frequency of pedestrian gaze observed in the vehicle-pedestrian interaction samples

Occurrence frequency	Pedestrian gaze behavior		
	No gaze	Once	Twice
Number of vehicle-pedestrian sample	11	102	74

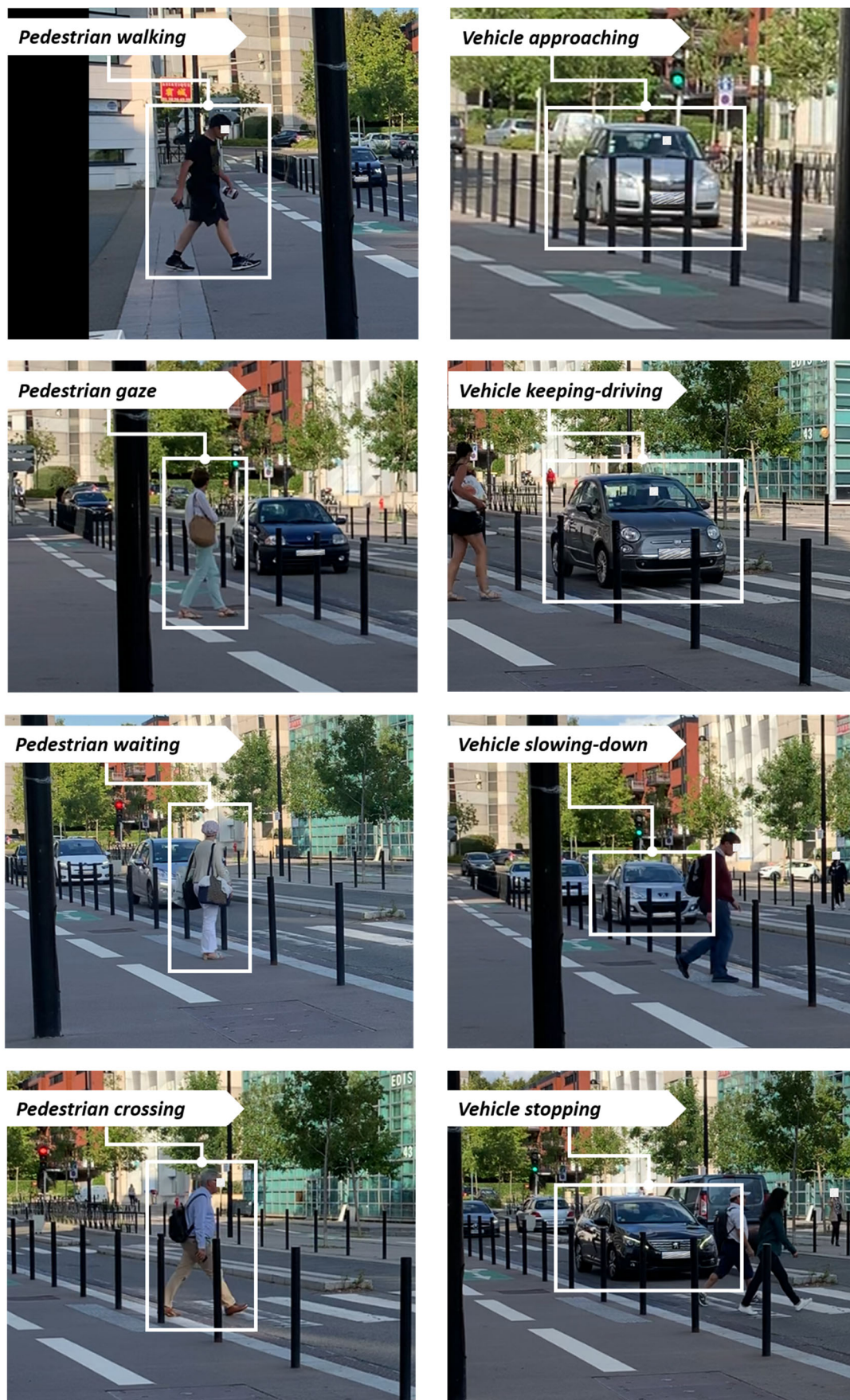


Fig. 4.5 Examples of video frames which contain the eight recognized vehicle and pedestrian behaviors in the interaction.



Fig. 4.6 Pedestrian gaze with the different occurrence frequency in the vehicle-pedestrian interaction: no gaze (a), gaze happening once (c) gazes happening twice (b)(d).

4.4.2 Vehicle and Pedestrian Behavioral Sequences

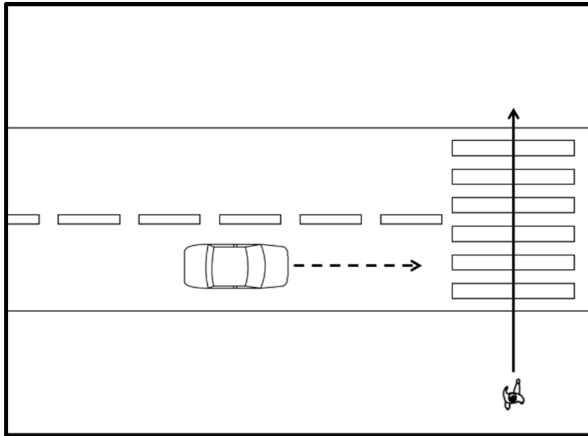
By noting the behaviors and their occurrence order, including pedestrian walking, pedestrian waiting, pedestrian crossing, vehicle approaching, vehicle keeping-driving, vehicle slowing-down, and vehicle stopping, seven scenarios of the vehicle-pedestrian interaction around the crosswalk were observed and categorized with respect to the different behavioral sequences (see Table 4.2 and Fig. 4.7).

Depending on whether the vehicle carried out the slowing-down behavior to yield to the pedestrian, the seven observed scenarios can be divided into two scenario groups: yielding type scenarios and non-yielding type scenarios. The yielding type scenarios include the scenarios #1-4 and the non-yielding type scenarios include the scenarios #5-7. As regards the yielding type scenarios, more details are found from our review. In the scenario #1 (44/187 samples), it is notable that both the vehicle and the pedestrian did not interrupt their moving status in their interaction around the crosswalk. On one side, the pedestrian approached towards the crosswalk, then cross directly the road without waiting at the curb. On the other side, the vehicle which allowed the pedestrian to cross in priority started the slowing-down from a long distance to the pedestrian without coming to a complete stopping. The scenario #2 (38/187 samples) was similar to the scenario #1. The sole difference observed between them is that the vehicle which yielded to the pedestrian slowed down until a complete stopping when the pedestrian crossed

the road. In the scenario 3 which rarely existed in our collected interaction samples (4/187 samples), an ambiguous mutual understanding seems to happen between the pedestrian and the vehicle. It is observed that the vehicle started the slowing-down from a relatively close distance to the pedestrian who waited at the curb. While the vehicle continued to slow down even until a much low speed, the pedestrian still waited at the curb for a little while before crossing the road. After the passage of the pedestrian through the crosswalk, the vehicle which did not come to a complete stopping passed through the crosswalk. In the scenario #4 (21/187 samples), the vehicle started the slowing-down from a relatively close distance to the pedestrian as well. The pedestrian waited at the curb for the vehicle stopping. After the vehicle complete stopping, the pedestrian crossed the road. As regards the non-yielding type scenarios, we observed two different situations consisting of no need to yield and fail to yield. What is notable in the scenario #5 (38/187 samples) is that the approaching vehicle was still far from the crosswalk when the walking pedestrian arrived at the curb. The pedestrian had enough time to cross the road and the vehicle did not need to yield to the pedestrian by slowing down or stopping. The situation was also no need to yield in the scenario #6 (34/187 samples), in which the pedestrian walked on the pavement towards the crosswalk when the vehicle already arrived at the crosswalk. Then, the vehicle kept driving and passed through the crosswalk directly without slowing down. After the passage of the vehicle through the crosswalk, the pedestrian arrived next to the crosswalk and crossed the road. In the scenario #7 (8/187 samples), it is observed that the pedestrian waited at the curb and the vehicle which was close to the pedestrian kept driving and passed through the crosswalk. The pedestrian had to remain standstill at the curb and let the vehicle pass firstly. Taking account of the vehicle-pedestrian interaction samples which correspond respectively to the above seven scenarios (see Fig. 4.8), it can be summarized that there were 31.6% of the vehicles coming to a complete stop to yield to the pedestrian (scenario #2, #4) and 25.7% slowed down their speed to allow the pedestrian to cross the road

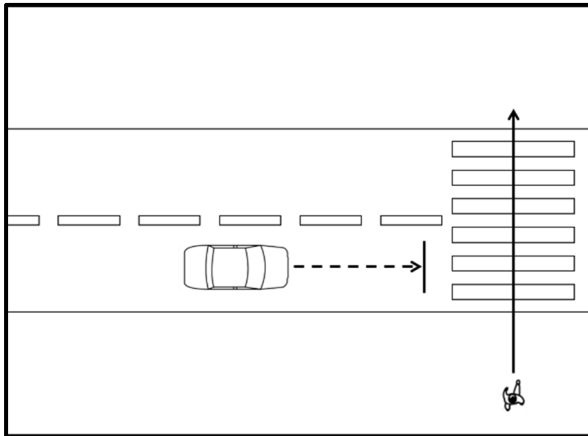
Table 4.2 Summary of the seven observed scenarios of the vehicle-pedestrian interaction around the urban crosswalk

N° scenario	Number of vehicle- pedestrian interaction samples	Labeled typical behavior						
		Pedestrian				Vehicle		
		<i>Walking</i>	<i>Waiting</i>	<i>Crossing</i>	<i>Approaching</i>	<i>Keeping-driving</i>	<i>Slowing-down</i>	<i>Stopping</i>
#1	44	×		×	×		×	
#2	38	×		×	×		×	×
#3	4	×	×	×	×		×	
#4	21	×	×	×	×		×	×
#5	38	×		×	×			
#6	34	×		×	×	×		
#7	8	×	×	×	×	×		



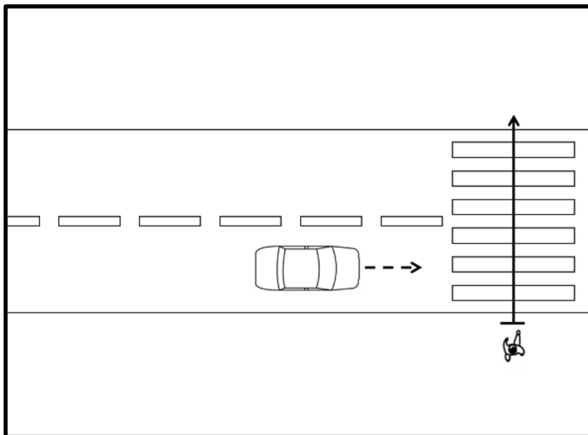
In the scenario #1:

1. The pedestrian walked towards the crosswalk, meanwhile the vehicle approached towards the crosswalk.
2. The pedestrian crossed the road directly, meanwhile the vehicle slowed down.
3. The vehicle passed through the crosswalk.



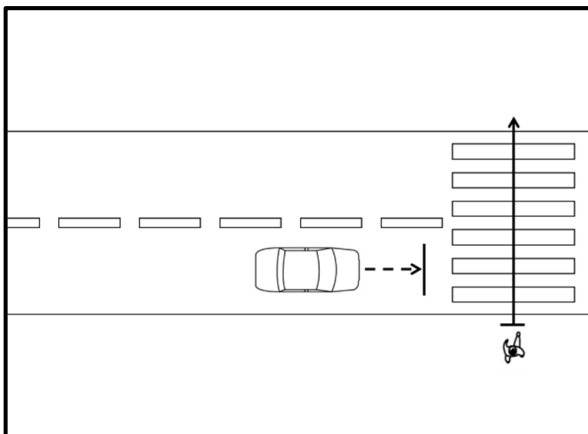
In the scenario #2:

1. The pedestrian walked towards the crosswalk, meanwhile the vehicle approached towards the crosswalk.
2. The pedestrian crossed the road directly, meanwhile the vehicle slowed down until a complete stopping.
3. The vehicle passed through the crosswalk.



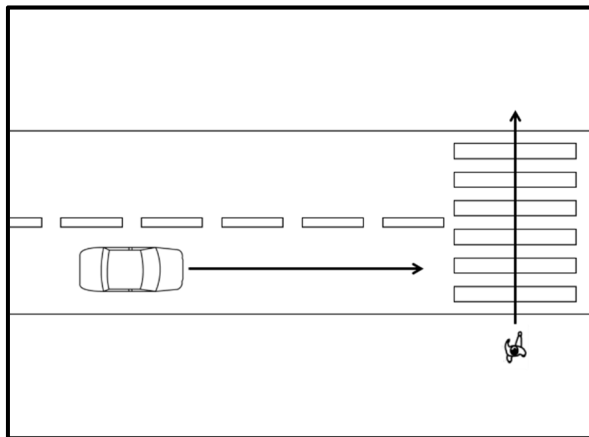
In the scenario #3:

1. The pedestrian walked towards the crosswalk, meanwhile the vehicle approached towards the crosswalk.
2. The pedestrian waited at the curb, meanwhile the vehicle slowed down.
3. The pedestrian crossed the road, meanwhile the vehicle slowed down.
4. The vehicle passed through the crosswalk.



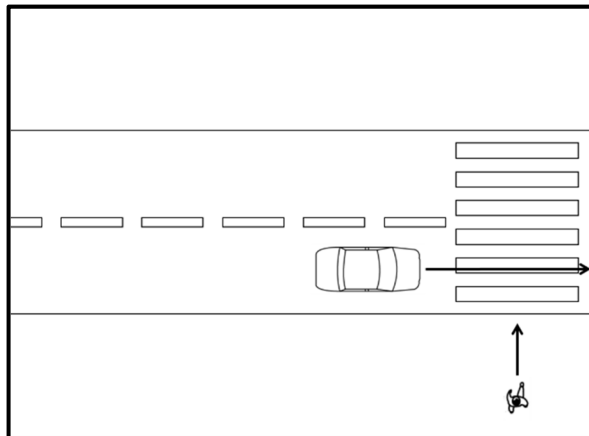
In the scenario #4:

1. The pedestrian walked towards the crosswalk, meanwhile the vehicle approached towards the crosswalk.
2. The pedestrian waited at the curb, meanwhile the vehicle slowed down until a complete stopping.
3. The pedestrian crossed the road, meanwhile the vehicle remained stopping.
4. The vehicle passed through the crosswalk.



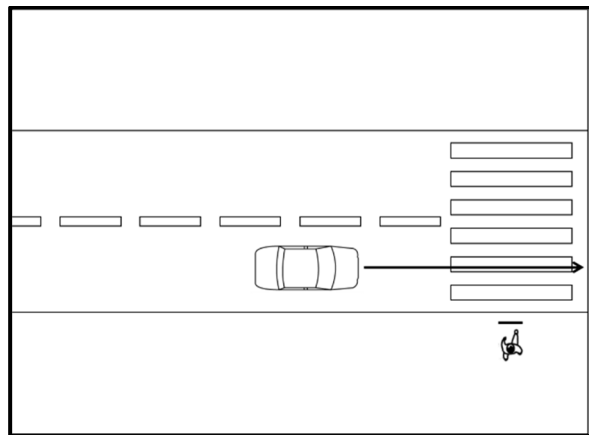
In the scenario #5:

1. The pedestrian walked towards the crosswalk, meanwhile the vehicle approached towards the crosswalk.
2. The pedestrian crossed the road, meanwhile the vehicle still approached towards the crosswalk.
3. The vehicle passed through the crosswalk.



In the scenario #6:

1. The pedestrian walked towards the crosswalk, meanwhile the vehicle approached towards the crosswalk.
2. The pedestrian still walked towards the crosswalk, meanwhile the vehicle kept driving and passed through the crosswalk.
3. The pedestrian crossed the road.



In the scenario #7:

1. The pedestrian walked towards the crosswalk, meanwhile a vehicle approached towards the crosswalk.
2. The pedestrian waited at the curb, meanwhile the vehicle kept driving and passed through the crosswalk.
3. The pedestrian crossed the road.

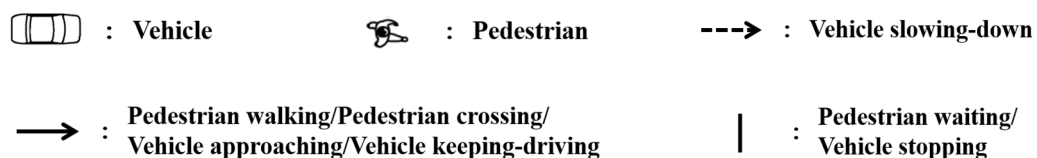


Fig. 4.7 Illustration and description of the seven observed scenarios of the vehicle-pedestrian interaction around the urban crosswalk categorized with respect to the different behavioural sequences.

(scenario #1, #3). 4.3% of the vehicles failed to yield to the pedestrian when they were obliged to (scenario #7). There were also 38.5% of the vehicles which did not need to yield to the pedestrian (scenario #5, #6). On the other hand, up to 43.9% of the pedestrians did not wait at the curb and crossed directly the road prior to the vehicle which slowed down to yield to them (scenario #1, #2). 13.4% of the pedestrians waited firstly at the curb and then crossed the road prior to the vehicle which slowed down (scenario #3, #4). Besides, 20.3% of the pedestrians did not wait at the curb and crossed directly the road prior to a non-yielding vehicle (scenario #5). Additionally, there were 22.5% of the pedestrians who achieved their road-crossing task after the passage of the vehicle through the crosswalk (scenario #6, #7).

4.5 Discussion: Interpretation on the Vehicle and Pedestrian Behaviors

4.5.1 On the Side of Pedestrians

As the results demonstrate, pedestrian gazes were widely observed in the collected vehicle-pedestrian interaction samples. Notably, it seems that pedestrians carried out this visual

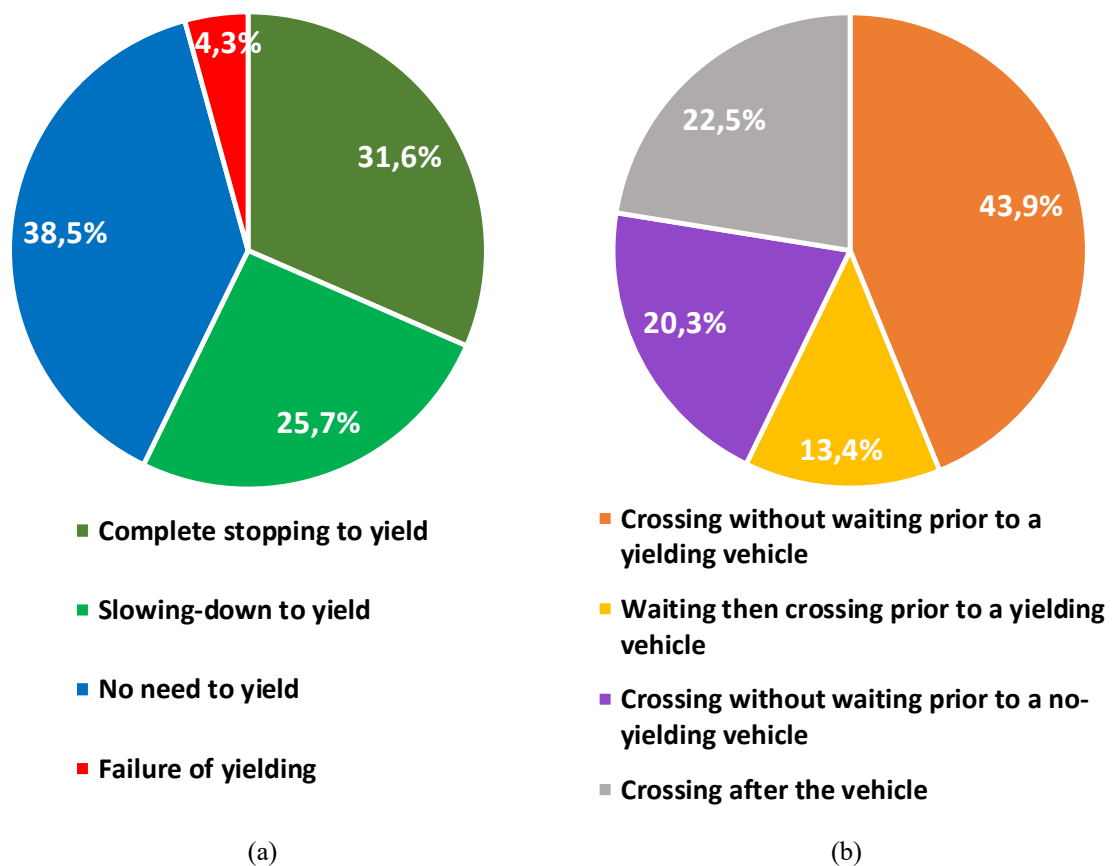


Fig. 4.8 Statistical summary of the vehicle (a) and pedestrian (b) behaviors in the vehicle-pedestrian interaction around the unsignalized urban crosswalk.

behavior spontaneously. This may be attributed to its indispensability for safety and its benefit for time-saving. When pedestrians prepare to cross the road, their visual scanning and their gazes towards the vehicle act for providing pedestrians with information about the vehicle, including vehicle speed and distance from the vehicle to the pedestrian [100][127]. This is indispensable for pedestrians who are with the road-crossing task to assess the vehicle status and intention [177].

Additionally, we observed that the pedestrian gaze could occur once or twice in the vehicle-pedestrian interaction. This observation can also be interpreted by the indispensability of gaze behavior. In the interaction samples with twice gazes, the pedestrian carried out a primary gaze to look for information about the vehicle which might be not sufficient for making the crossing decision. Thereby, the pedestrian had to rely on a secondary gaze to explore the vehicle status and intention once more. In the samples with once gaze, we assume that the information provided by the single gaze was adequate for pedestrians to confirm their crossing decision.

Furthermore, in the condition where the information collected by the gaze behavior is clear for the pedestrian to determine that there is an acceptable gap between the vehicle and the pedestrian for a safe crossing, the pedestrian who choose to cross without waiting at the curb can reduce their cost time for realizing the road-crossing task. This assumption attached well to

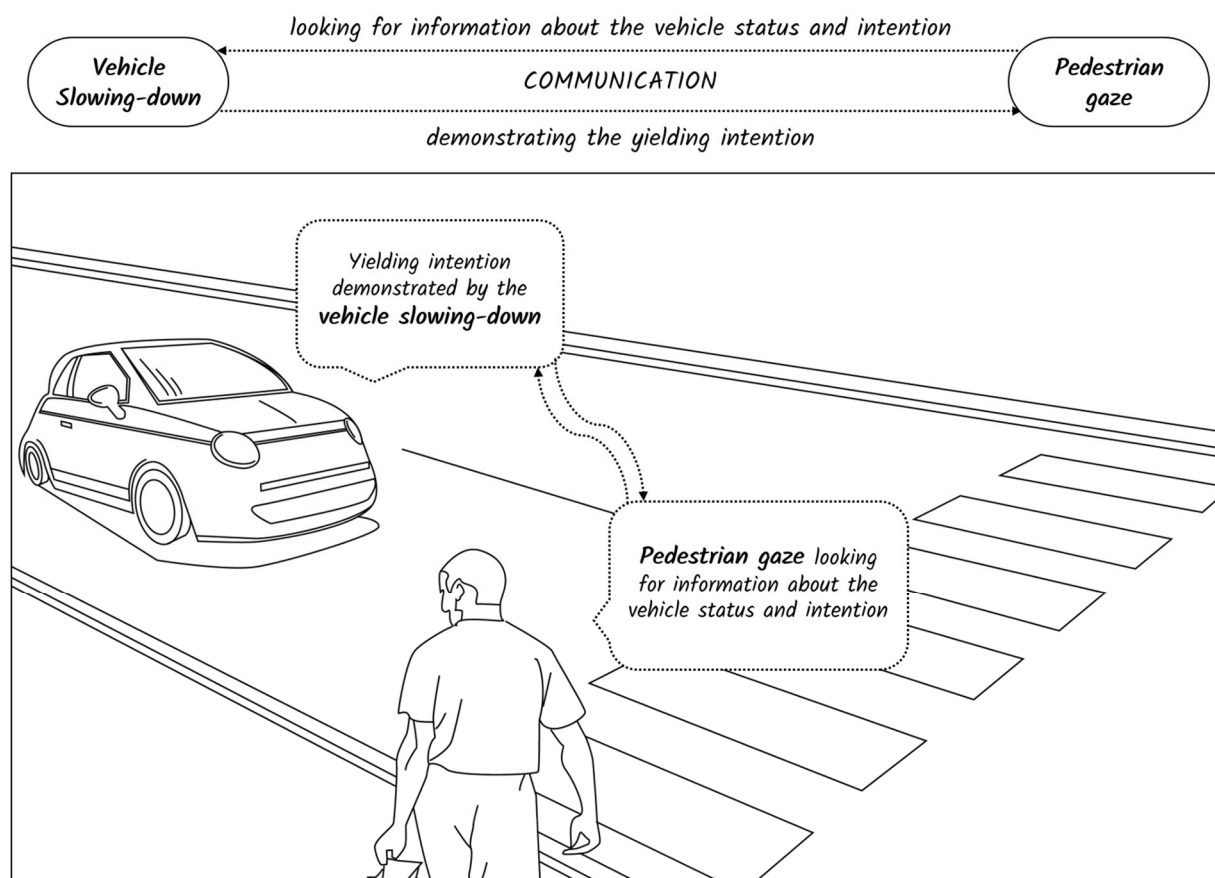


Fig. 4.9 Pedestrian gaze and vehicle slowing-down contribute to constituting a communication between the pedestrian and vehicle in their interaction.

the observed yielding-type scenarios #1, #2 and non-yielding type scenario #5 in which the pedestrian who initially walked on the pavement crossed directly the road without waiting.

Overall, we argue that the pedestrian gaze contributes to constituting a communication between the vehicle and the pedestrian in their interaction, as this visual behavior can be regarded as one side of the communication channel that pedestrians relied on to look for information about the vehicle status and intentions (see Fig. 4.9). Based on this, we suggested considering the pedestrian gaze as a significant behavior for the communication in the vehicle-pedestrian interaction. In order to further understand the behavioral pattern of pedestrian gaze, the following quantification was carried out with this visual behavior. As we observed that the pedestrian gaze could occur once or twice in the vehicle-pedestrian interaction, we suggested giving new labels for the gaze behavior. To distinguish them, the secondary gaze in the samples with twice gazes was labeled as the late gaze, while the primary gaze was labeled as the early gaze. In the samples with once gaze, the single gaze was labeled as the late gaze.

As regards whether pedestrians carried out a waiting or a crossing behavior, the different effects of vehicle slowing-down on it were noticed (see Fig. 4.10). Among the collected interaction samples, 43.9% of the pedestrians crossed directly the road without waiting at the curb prior to the vehicle which slowed down to yield. Otherwise, there were 13.4% of the pedestrians who waited at the curb and then crossed the road prior to the vehicle which slowed down. The motives lying behind these different pedestrian behaviors may be interpreted by the roles of vehicle speed variation and distance from the vehicle to the pedestrian. Agreeing with the existing research works concluding that the vehicle speed variation act as an implicit indicator of the vehicle intention and the distance from the vehicle to the pedestrian is a factor influencing the pedestrian crossing decision [54][104][129], we assume that the vehicle slowing-down is a perceivable “signal” of yielding intention and such signal in combination with the distance from the vehicle to the pedestrian demonstrates the information required by pedestrians for determining whether there is an acceptable gap to safely cross the road. In the scenario #1 where the vehicle demonstrated the signal, i.e. slowing-down, from a long distance to the pedestrian, the pedestrian could perceive and understand early that a far vehicle with the yielding intention would leave them a sufficient gap to cross the road in priority. Thereby, the pedestrian tended to cross the road without waiting for saving time. Conversely, in the scenario #4 where the vehicle carried out the slowing-down from a close distance to the pedestrian, the retard of getting this signal of yielding intention would not allow pedestrians to make a crossing decision in time. Hence, the pedestrian had to wait at the curb to look for more information in order to be sure that no risk of crossing existed.

In view of the above interpretation, we argue that the vehicle slowing-down contributes to a communication between the vehicle and the pedestrian. This implicit behavior can be regarded as one other side of the communication channel which performs as a signal demonstrating the vehicle yielding intention (see Fig. 4.9). Besides, the distance from the vehicle to the pedestrian should always be taken into account as the basic information exchanged between the vehicle and pedestrian. Based on these, we suggested considering the vehicle showing down as a significant behavior for the communication in the vehicle-pedestrian interaction. The quantitation was carried out with the vehicle showing-down in the next for investigating its behavioral pattern.

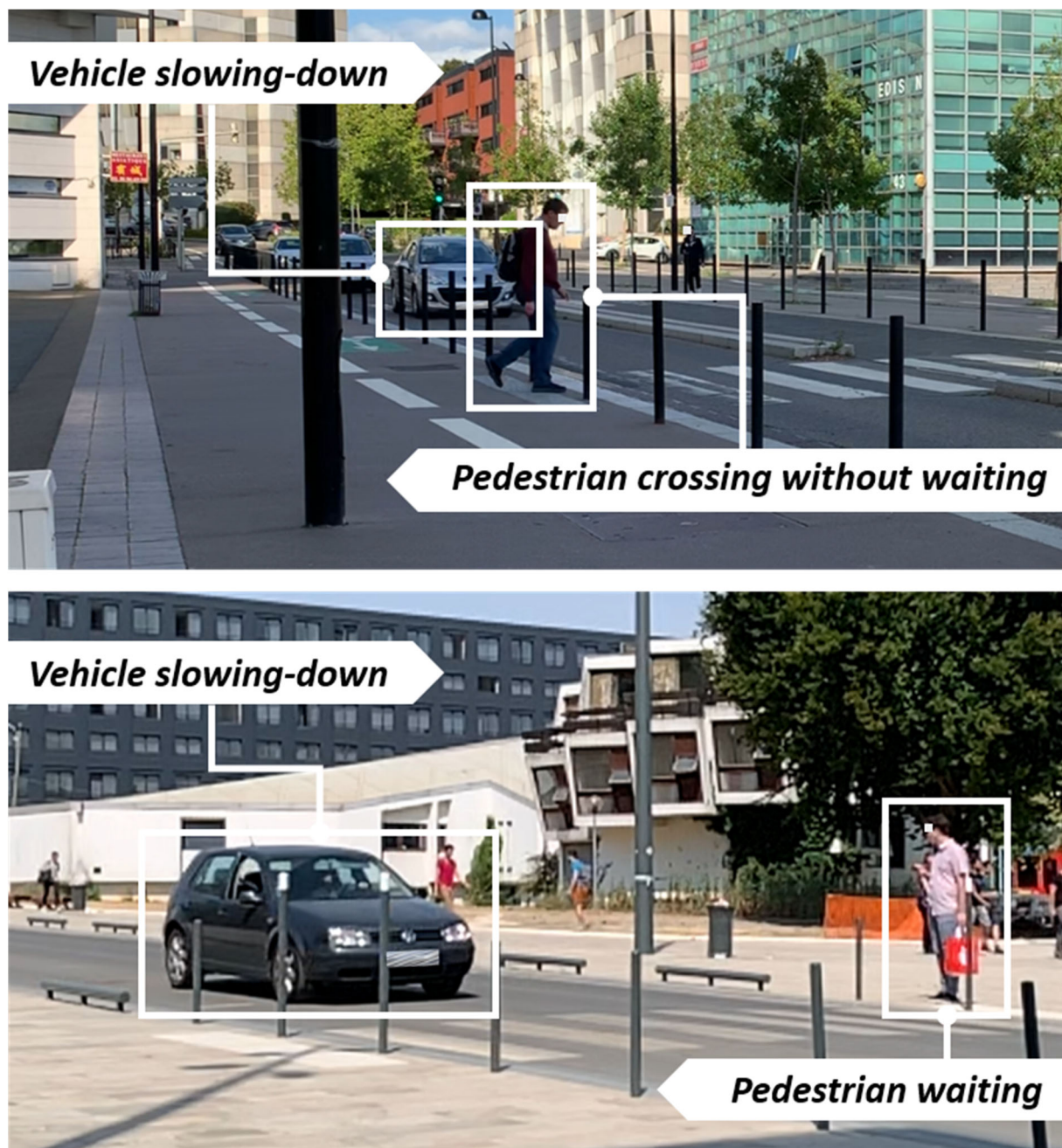


Fig. 4.10 Different effects of vehicle slowing-down on the pedestrian crossing or waiting behaviors.

4.5.2 On the Side of Vehicles

For the vehicle which controlled by the human driver inside, our review of the vehicle-pedestrian samples indicates that 4.3% of the vehicles failed to yield to the pedestrian when they were obliged to. This concerned few drivers who did not respect the traffic rule and might bring danger to vulnerable pedestrians.

Moreover, the results show that among the vehicles which yielded to the pedestrian, 31.6% of them came to a complete stopping, whereas 25.7% of them slowed down without a complete stopping. For the complete stopping, this vehicle behavior ideally fulfills pedestrians' need for feeling safety in the road-crossing [54]. For the slowing-down without a complete stopping,

this vehicle behavior can be explained by drivers' motive of avoiding restarting the vehicle from a stopping status.

In order to organize the passage with the pedestrian around the crosswalk, it can be assumed that the driver sends a signal demonstrating the yielding intention to the pedestrian by the means of slowing down the vehicle. The pedestrian who received this signal can thus decide how to behave to interact with the vehicle. In response to the pedestrian decision and behavior, the driver can then adjust the vehicle dynamic. When facing the pedestrian who decides to cross directly the road after perceiving the vehicle slowing-down, the driver can maintain the vehicle slowing-down to allow the pedestrian to pass through the road in priority. Once the passage of the pedestrian is accomplished, the driver can then accelerate the vehicle to pass through the crosswalk. For this organization of passage between the vehicle and the pedestrian, both these two road users do not need to interrupt their moving status. This establishes an efficient and fluid vehicle-pedestrian interaction. Among the recognized scenarios of the vehicle-pedestrian interaction around the crosswalk, the above assumption corresponds well to what is observed in the scenario #1.

However, the ambiguous situation may appear if the driver insists an unsuitable vehicle slowing-down without coming to a complete stopping. In the scenario #3 where the vehicle slowing-down was employed from a relatively close distance to the pedestrian, the pedestrian is observed to wait at the curb instead of crossing the road directly. Then, when the vehicle kept slowing down even to a much low speed, it is noticed that the pedestrian hesitated for a while and crossed the road. This can be interpreted by the fact that a late vehicle slowing-down carried out from a close distance to the pedestrian did not enable the pedestrian to have a firm crossing decision. From the point of view of the pedestrian, a close distance from the vehicle to the pedestrian meant an unacceptable gap to cross the road. This is in conflict with the yielding intention demonstrated by the vehicle slowing-down, which caused consequently the hesitation to the pedestrian. As a matter of fact, the conflict lying behind the scenario #3 reveals the importance of communicating the vehicle yielding intention in time, which is fundamental for the clear vehicle-pedestrian interaction.

Furthermore, the count of the different scenarios of the vehicle-pedestrian interaction around the crosswalk shows that there were 38.5% of the vehicles did not need to yield to the pedestrian. In the scenario #5, it is found that the vehicle which was much far from the pedestrian did not slow down while approaching towards the crosswalk. On the other hand, the pedestrian crossed directly the road without waiting at the curb. For this non-yielding type scenario, the much long distance between the vehicle and the pedestrian means an adequate gap which is available between these two road users. The pedestrian who gets the sense of such gap can freely achieve the road-crossing task prior to the vehicle, as it is clear that the vehicle will not arrive at the crosswalk regardless of a maintained speed without slowing down. During the passage of the pedestrian through the crosswalk, the approaching vehicle which does not bring any danger to the pedestrian has no need to yield. In the scenario #6, it is observed that the vehicle arrived at and passed through the crosswalk. Meanwhile, the pedestrian was still walking towards the crosswalk on the pavement. To interpret this non-yielding type scenario, it is straightforward that the vehicle has no need to wait the pedestrian for having an efficient and fluid traffic flow. It would still take the pedestrian some time to arrive at the curb and the vehicle at the same time already passed through the crosswalk. After the passage of vehicle, the pedestrian can then cross the road freely.

Table 4.3 Results of quantifying the vehicle-pedestrian interaction samples: position of the pedestrian relative to the vehicle at the time of the significant vehicle and pedestrian behaviors in terms of V2P distance and V2P angle

N° sample	Scenario type	Positional coordinate (Xv, Yv, Xp, Yp in meter), V2P distance (D in meter), V2P angle (α in degree)																	
		Pedestrian early gaze						Pedestrian late gaze						Vehicle slowing-down					
		Xv	Yv	Xp	Yp	D	α	Xv	Yv	Xp	Yp	D	α	Xv	Yv	Xp	Yp	D	α
1	yield	/	/	/	/	/	/	1.52	12.76	6.38	0.02	13.64	-20.97	1.54	12.26	6.38	0.022	13.17	-21.75
2	yield	1.53	16.58	-3.05	0.88	16.34	16.17	1.55	10.42	-1.91	-0.02	10.98	18.10	1.52	14.36	-2.62	-0.05	14.98	15.96
3	yield	4.45	39.22	-4.91	-5.59	45.78	11.86	4.51	18.75	-2.36	-4.56	24.29	16.40	1.50	10.82	-0.96	-2.98	14.01	10.09
4	yield	1.58	15.03	8.73	3.81	13.34	-32.81	1.54	9.82	7.37	0.52	10.99	-32.27	1.48	9.82	7.37	0.52	10.99	-32.27
5	yield	/	/	/	/	/	/	1.49	14.17	6.38	-1.11	16.04	-17.72	1.53	6.28	6.38	-1.11	8.85	-33.46
6	yield	1.52	39.22	10.38	-1.32	41.50	-12.36	1.48	13.51	6.56	-0.83	15.20	-19.44	1.47	5.08	6.56	-0.83	7.78	-40.59
7	yield	1.48	25.30	8.96	-2.85	29.12	-14.85	1.52	14.36	6.74	-2.46	17.61	-17.31	1.48	7.18	6.00	-2.13	10.34	-25.81
8	yield	1.61	25.36	-2.47	-1.58	27.24	8.59	1.59	19.95	-0.78	-1.63	21.71	6.30	1.58	8.95	1.6	-1.61	10.56	0.00
9	yield	/	/	/	/	/	/	1.61	24.94	-4.88	-1.61	27.32	13.72	1.64	13.78	-2.1	-2.52	16.71	12.79
10	yield	1.57	21.65	-4.48	-1.97	24.39	14.44	1.62	12.81	-2.26	-2.12	15.42	14.50	1.64	8.70	-0.44	-2.04	10.93	10.76
11	yield	1.63	24.53	-5.48	-1.64	27.11	15.14	1.61	14.45	-2.17	-3.60	18.43	11.80	1.63	5.50	1.54	-3.05	8.55	0.40
12	yield	/	/	/	/	/	/	1.60	10.28	6.07	-0.51	12.73	-20.56	1.62	10.28	6.07	-0.51	11.67	-22.51
13	yield	1.60	23.94	-1.62	-1.92	26.05	7.10	1.62	8.41	-1.77	-1.92	10.86	18.08	1.58	15.11	-1.77	-1.92	17.36	11.20
14	yield	1.62	22.16	-4.18	-0.43	23.31	14.36	1.59	7.85	0	-2.00	9.97	9.23	1.62	8.95	-0.44	-1.95	11.08	10.61
15	yield	1.58	23.35	-2.98	-2.93	26.67	9.89	1.57	7.25	-0.30	-3.82	11.23	9.74	1.58	10.85	-1.32	-3.31	14.45	11.66
16	yield	/	/	/	/	/	/	1.62	7.25	-0.66	-3.2	10.67	11.89	1.63	10.85	-1.32	-2.24	13.41	12.58
17	yield	1.62	12.54	-2.82	0.1	13.20	19.57	1.63	3.87	1.01	-0.5	4.40	7.70	1.64	12.54	-2.82	0.10	13.20	19.57
18	yield	1.60	23.43	-2.59	-0.91	24.69	9.77	1.61	6.32	-0.63	-1.82	8.44	15.33	1.59	9.78	-0.63	-1.82	11.81	10.89
19	yield	1.59	29.00	-3.57	-1.54	30.97	9.61	1.60	14.73	-0.71	-2.00	16.88	7.86	1.57	15.89	-1.26	-1.92	18.03	9.13
20	yield	/	/	/	/	/	/	1.61	16.31	-2.98	-2.93	19.77	13.39	1.63	5.66	0	-3.17	8.97	10.28
21	yield	1.61	29.00	8.65	-1.27	31.08	-13.11	1.63	16.31	4.83	-1.31	15.34	-12.16	1.60	5.66	-0.15	-0.98	6.86	14.78
22	yield	1.59	22.16	10.65	-4.18	27.85	-18.97	1.57	8.41	5.06	-2.55	12.70	-26.07	1.60	10.58	7.18	-3.08	14.75	-22.23
23	yield	1.57	22.16	11.15	-3.33	27.22	-20.54	1.63	8.41	6.46	-1.50	11.03	-26.14	1.63	10.58	7.18	-2.08	13.83	-23.79
24	yield	/	/	/	/	/	/	1.58	7.55	6.76	-1.42	10.34	-29.92	1.57	11.61	8.00	-1.70	14.76	-25.69
25	yield	/	/	/	/	/	/	1.56	13.33	-2.38	0.33	13.59	17.03	1.62	14.48	-3.07	0.16	15.06	18.07
26	yield	1.62	15.57	-4.31	-1.58	18.14	19.02	1.61	7.96	-2.81	-1.51	10.44	24.98	1.57	13.07	-3.97	-1.38	15.48	21.09
27	yield	/	/	/	/	/	/	1.60	15.01	-2.99	-2.62	18.21	14.60	1.61	13.07	-2.99	-2.62	16.34	16.31
28	yield	/	/	/	/	/	/	1.50	18.02	-4.48	-2.35	21.25	16.62	1.58	10.61	-3.06	-2.15	13.58	20.07
29	yield	/	/	/	/	/	/	1.61	13.62	-3.63	-3.12	17.53	17.35	1.63	10.61	-3.04	-3.19	14.55	18.59
30	yield	/	/	/	/	/	/	1.63	10.15	-2.69	-0.91	11.86	21.21	1.64	8.46	-2.38	-0.91	10.18	23.02

N° sample	Scenario type	Positional coordinate (Xv, Yv, Xp, Yp in meter), V2P distance (D in meter), V2P angle (α in degree)																	
		Pedestrian early gaze						Pedestrian late gaze						Vehicle slowing-down					
		Xv	Yv	Xp	Yp	D	α	Xv	Yv	Xp	Yp	D	α	Xv	Yv	Xp	Yp	D	α
31	yield	1.61	24.39	-2.98	-3.62	28.38	9.29	1.62	7.14	-0.87	-3.69	11.10	12.85	1.63	2.65	-0.48	-4.02	6.98	17.33
32	yield	1.62	31.14	8.29	-1.97	33.77	-11.42	1.60	18.02	6.59	-1.83	20.46	-14.11	1.61	10.61	6.29	-1.78	13.24	-20.74
33	no-yield	/	/	/	/	/	/	1.52	6.51	8.38	-2.72	11.51	-36.72	/	/	/	/	/	/
34	no-yield	/	/	/	/	/	/	1.50	27.57	-0.41	2.35	25.29	4.33	/	/	/	/	/	/
35	no-yield	/	/	/	/	/	/	1.54	23.09	-1.12	1.29	21.95	6.85	/	/	/	/	/	/
36	no-yield	/	/	/	/	/	/	1.51	7.17	-4.62	-0.27	9.63	39.46	/	/	/	/	/	/
37	no-yield	/	/	/	/	/	/	1.48	33.63	-1.84	1.49	32.31	5.93	/	/	/	/	/	/
38	no-yield	/	/	/	/	/	/	1.49	39.09	-0.56	0.47	38.67	3.05	/	/	/	/	/	/
39	no-yield	/	/	/	/	/	/	1.60	19.44	-1.82	-0.91	20.63	9.54	/	/	/	/	/	/
40	no-yield	/	/	/	/	/	/	1.63	29.00	-2.48	0.28	29.00	8.09	/	/	/	/	/	/
41	no-yield	1.60	31.14	-4.48	0.16	31.57	11.11	1.60	19.44	-0.87	-1.92	21.50	6.60	/	/	/	/	/	/
42	no-yield	1.60	21.65	-2.98	-1.44	23.53	11.22	1.59	17.73	-1.48	-1.92	19.88	8.91	/	/	/	/	/	/
43	no-yield	/	/	/	/	/	/	1.60	0.44	-4.48	0.16	6.09	87.41	/	/	/	/	/	/
44	no-yield	1.61	23.94	-0.91	-2.93	26.98	5.34	1.62	14.25	-0.91	-2.93	17.36	8.31	/	/	/	/	/	/
45	no-yield	1.52	24.29	10.65	2.45	23.67	-22.74	1.53	1.92	7.24	0.88	5.83	-79.78	/	/	/	/	/	/
46	no-yield	/	/	/	/	/	/	1.54	7.02	-5.32	-5.28	14.06	29.02	/	/	/	/	/	/
47	no-yield	/	/	/	/	/	/	1.57	6.32	8.37	-1.58	10.40	-40.61	/	/	/	/	/	/
48	no-yield	/	/	/	/	/	/	1.59	10.01	-1.8	-3.38	13.81	14.25	/	/	/	/	/	/
49	no-yield	/	/	/	/	/	/	1.63	5.77	-3.72	-1.52	9.02	36.14	/	/	/	/	/	/
50	no-yield	/	/	/	/	/	/	1.56	1.85	-2.98	-0.91	5.34	58.97	/	/	/	/	/	/
51	no-yield	/	/	/	/	/	/	1.59	14.73	-3.57	-1.54	17.07	17.63	/	/	/	/	/	/
52	no-yield	/	/	/	/	/	/	1.63	14.45	-4.48	-2.00	17.53	20.29	/	/	/	/	/	/
53	no-yield	/	/	/	/	/	/	1.61	11.71	9.83	-2.39	16.32	-30.28	/	/	/	/	/	/
54	no-yield	/	/	/	/	/	/	1.58	22.16	8.76	0.15	23.14	-18.02	/	/	/	/	/	/
55	no-yield	/	/	/	/	/	/	1.63	3.31	-4.16	-2.93	8.49	42.73	/	/	/	/	/	/
56	no-yield	/	/	/	/	/	/	1.59	3.31	-4.39	-2.15	8.10	47.68	/	/	/	/	/	/
57	no-yield	/	/	/	/	/	/	1.63	29.00	-2.10	-1.95	31.17	6.82	/	/	/	/	/	/
58	no-yield	1.60	31.14	7.18	-4.00	35.58	-9.02	1.62	29.00	6.06	-3.4	32.70	-7.84	/	/	/	/	/	/
59	no-yield	1.64	32.40	-3.94	-3.13	35.95	8.86	1.62	21.65	-0.94	-3.63	25.40	5.74	/	/	/	/	/	/
60	no-yield	/	/	/	/	/	/	1.61	29.00	-2.16	-2.46	31.68	6.82	/	/	/	/	/	/
61	no-yield	/	/	/	/	/	/	1.57	39.22	7.18	-0.74	40.34	-7.95	/	/	/	/	/	/
62	no-yield	/	/	/	/	/	/	1.63	24.83	-3.03	-1.26	26.49	10.06	/	/	/	/	/	/

For the interaction samples which have V2P angle (α) $\geq 0^\circ$, the involved pedestrians were coming from the right side of the vehicle.
For the interaction samples which have V2P angle (α) $< 0^\circ$, the involved pedestrians were coming from the left side of the vehicle

4.6 Results of Quantifying the Vehicle-Pedestrian Interaction

We proposed a perspective that the vehicle-pedestrian interaction can be quantified as the position of the pedestrian relative to the vehicle at the time of vehicle or pedestrian behaviors in terms of the V2P distance and V2P angle. In this study, the quantification was conducted with the pedestrian early gaze, the pedestrian late gaze, and the vehicle slowing-down which were suggested as the significant behaviors in the vehicle-pedestrian interaction. This selection is based on our previous assumption that the pedestrian gaze and the vehicle slowing-down contribute to constituting the communication of information in the vehicle-pedestrian interaction. Besides, compared to the existing research works which addressed the important behaviors in the vehicle-pedestrian interaction, it is noticed that we consistently headed towards the pedestrian gaze and the vehicle slowing-down [136][137]. Both of these show that it would be interesting to launch a study on these significant behaviors with a quantitative approach.

Unfortunately, not all the vehicle-pedestrian interaction samples are available for the quantification. The quantification requires the positional coordinates of vehicle and pedestrian to be extracted from the video frame containing the behavior to be studied. However, for the interaction samples in which the vehicle behaviors were recognized on the road lane in the opposite direction to the camera, the achievable road markings in the captured video frame were not sufficient to employ the comparison procedure. In consequence, the data extraction was only launched for 62 exploitable interaction samples in which the approaching vehicles were on the road lane in the forward direction to the camera. Relying on the positional coordinates of vehicle and pedestrian extracted from the exploitable interaction samples, the positions of the pedestrian relative to the vehicle in terms of V2P distance and V2P angle at the time of the pedestrian early gaze, the pedestrian late gaze, and the vehicle slowing-down were calculated (see Table 4.3). By distinguishing the interaction samples corresponding to the yielding type scenarios #1-4 from those corresponding to the non-yielding type scenarios #5-7, Fig. 4.11, Fig. 4.13, Table 4.4, and Table 4.5, illustrate the distribution of the three significant behaviors as a function of V2P distance and V2P angle. In addition, Fig. 4.12 and Fig. 4.14 present the empirical probability density of the three significant behaviors as a function of V2P distance and V2P angle.

4.6.1 Distribution and Probability Density of the Significant Behaviors in the Yielding Type Scenarios

For the scenarios #1-4 where the vehicle yielded to the pedestrian (see Fig. 4.11 and Table 4.4), it can be seen that no pedestrian early gaze and few pedestrian late gazes happened from 0 to 10 m for the V2P distance. Then, a large number of pedestrian late gazes were observed from 10 to 20 m. From 20 m, the pedestrians rarely had the late gaze, but the early gazes occurred more frequently. Taking account of the vehicle slowing-down, it can be noticed that few vehicles started the slowing-down from 0 to 10 m and the number was much higher when the V2P distance is between 10 to 20 m. Beyond 20 m, no vehicle slowing-down has been observed. Notably, the distribution of the vehicle slowing-down is similar to that of the pedestrian late gaze in terms of V2P distance. As regards the distribution of the significant behaviors from the

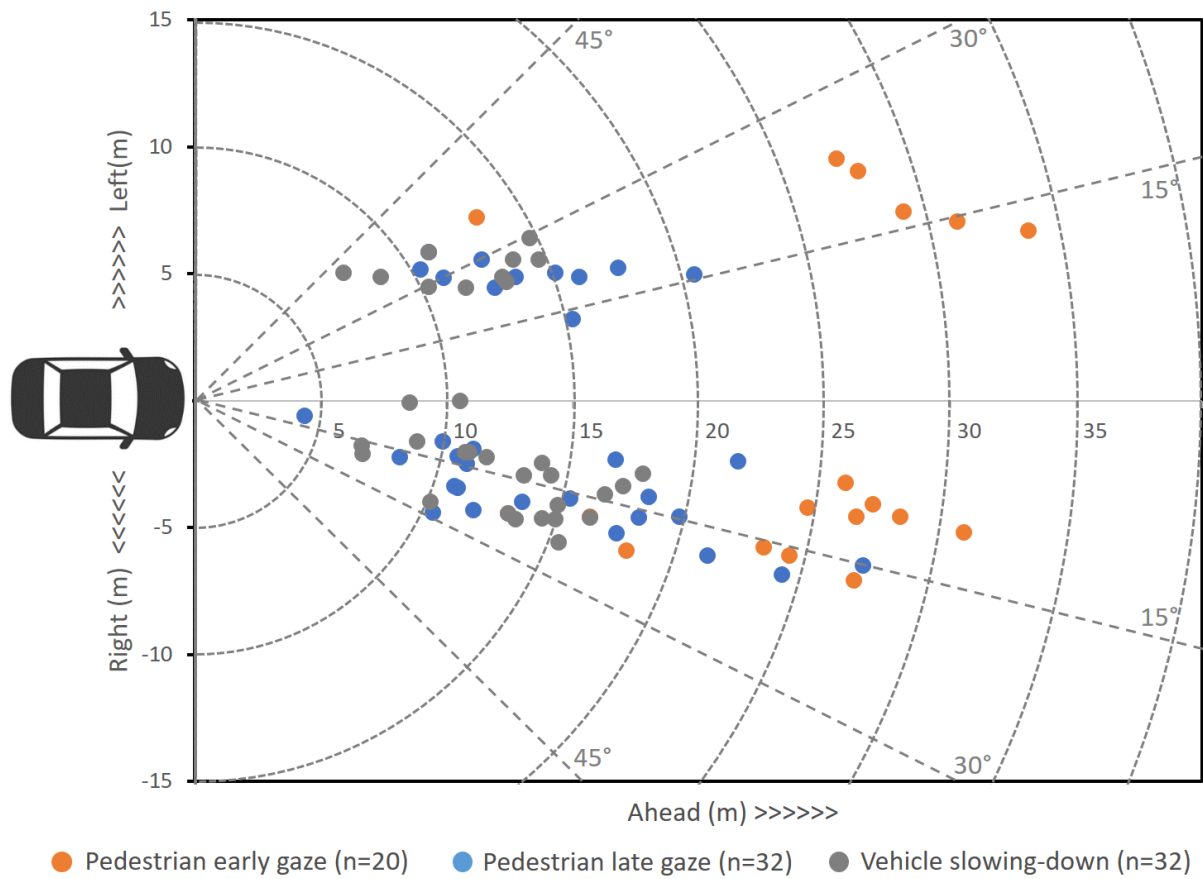


Fig. 4.11 Distribution of the pedestrian early gaze, the pedestrian late gaze, and the vehicle slowing-down as a function of V2P distance and absolute V2P angle in the yielding type scenarios.

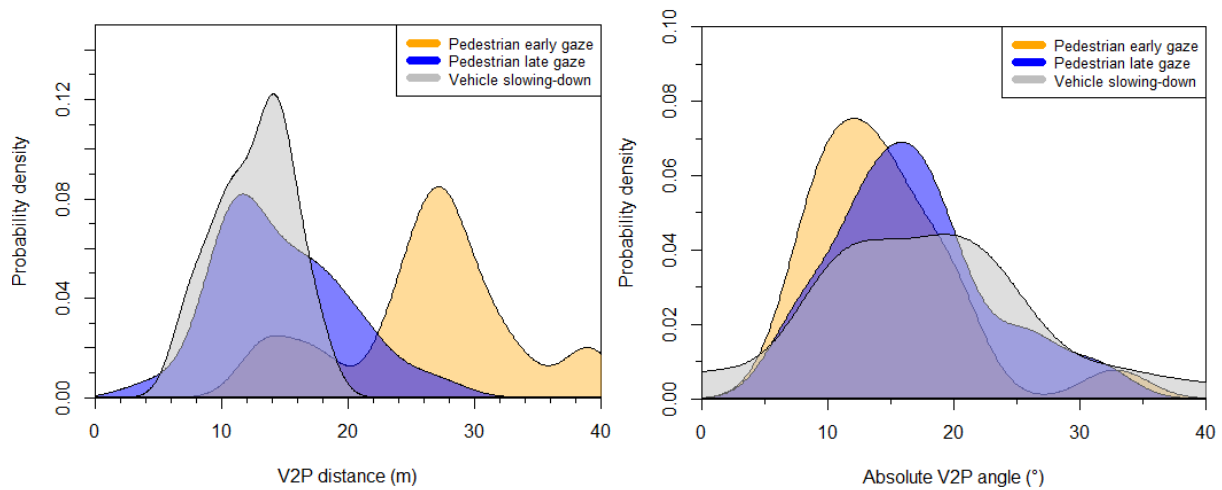


Fig. 4.12 Empirical probability densities of the pedestrian early gaze, the pedestrian late gaze, and the vehicle slowing-down as a function of V2P distance and absolute V2P angle in the yielding type scenarios.

perspective of absolute V2P angle, it can be noticed that lots of pedestrian early gazes, pedestrian late gazes, and vehicle slowing-downs happened from 0° to 15°. From 15° to 30°, there were a large number of pedestrian late gazes and vehicle slowing-downs. In the same

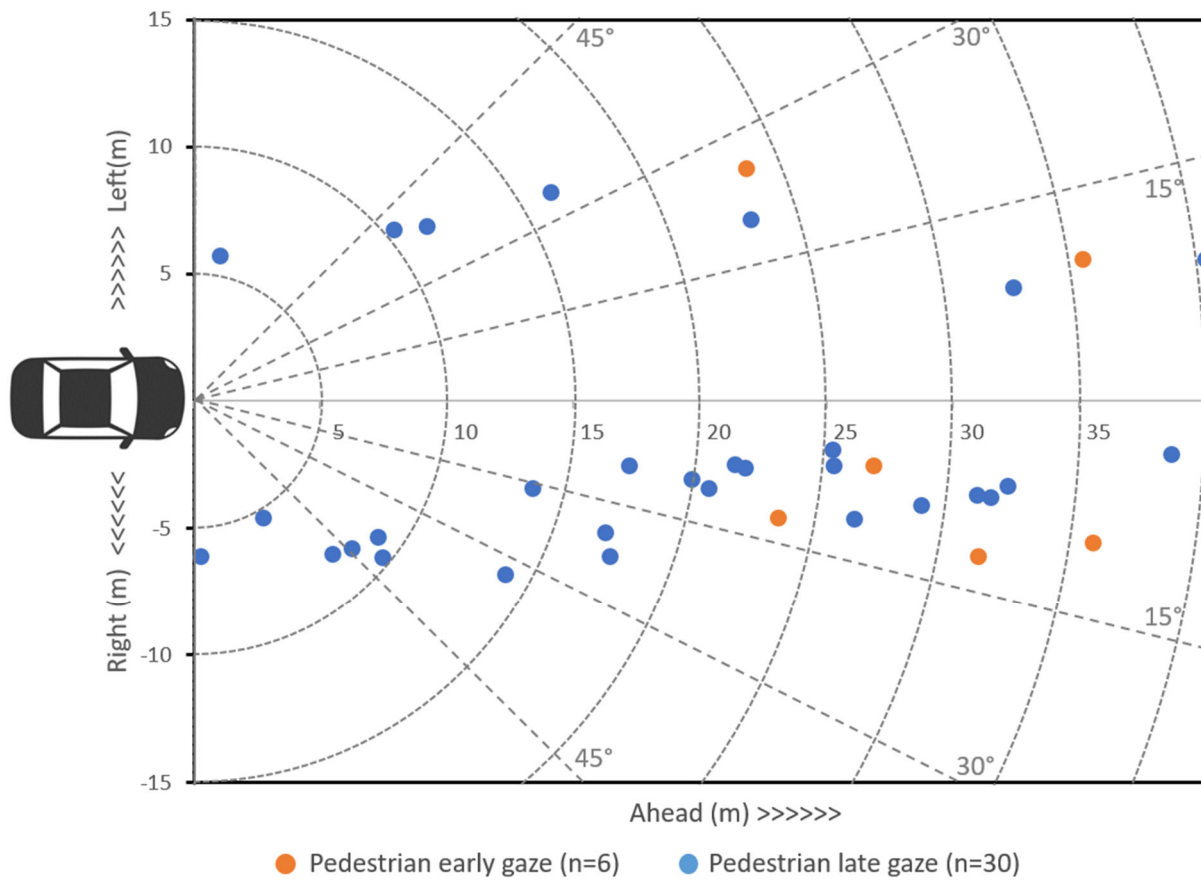


Fig. 4.13. Distribution of the pedestrian early gaze and the pedestrian late gaze as a function of V2P distance and absolute V2P angle in the non-yielding type scenarios.

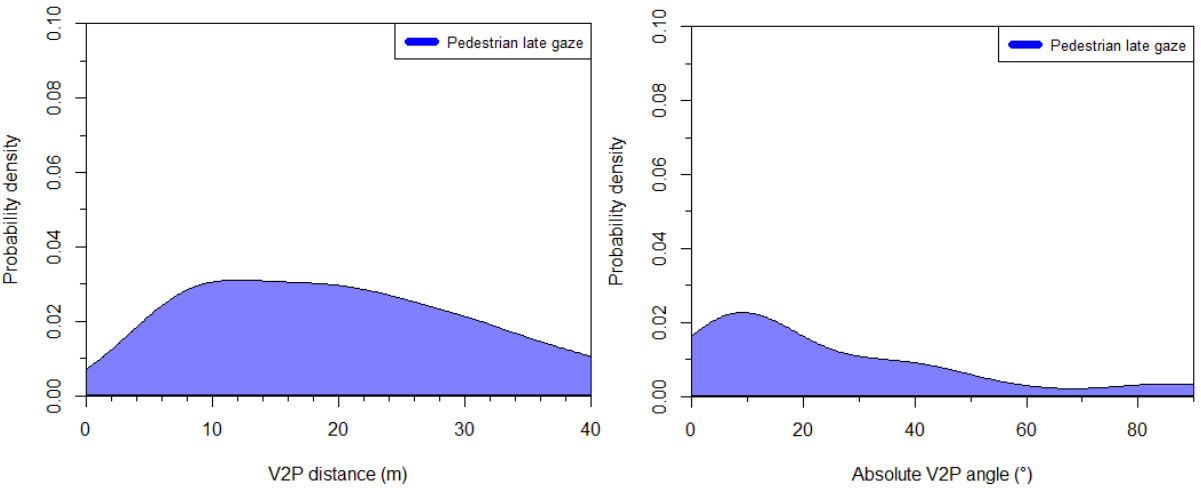


Fig. 4.14. Empirical probability density of the pedestrian late gaze as a function of V2P distance and absolute V2P angle in the non-yielding type scenarios.

interaction with the vehicle. Beyond 20 m for the V2P distance, few early gazes were observed. It is found that the late gazes occurred almost uniformly from 0 to 40 m. For the absolute V2P angle, there were many late gazes happening from 0° to 15°. From 15° up to 90°, their occurrence seemed to be infrequent but uniform.

Table 4.5 Distribution of the pedestrian early gaze and the pedestrian late gaze as a function of V2P distance and absolute V2P angle in the non-yielding type scenarios

Non-yielding type scenarios #5-7	Number of interaction samples with the significant behavior	V2P distance		
		0 – 10 m	10 – 20 m	> 20 m
	Pedestrian early gaze	0	0	6
Non-yielding type scenarios #5-7	Number of interaction samples with the significant behavior	Absolute V2P angle		
		0 – 15°	15° – 30°	> 30°
	Pedestrian early gaze	6	0	0
Non-yielding type scenarios #5-7	Number of interaction samples with the significant behavior	Absolute V2P angle		
		0 – 15°	15° – 30°	> 30°
	Pedestrian late gaze	15	4	11

The distribution of the pedestrian early and late gazes in the non-yielding type scenarios can be further verified by the empirical probability density functions (see Fig. 4.14). The early gaze was not treated here, as it occurred very rarely in the non-yielding type scenarios. For the late gaze, no clear pattern was recognized as a function of V2P distance and absolute V2P angle. What can be mentioned is that there was a little higher probability density for the late gaze situated in the zone from around 10 to 20 m. There was nearly no late gaze from around 45° to 90°.

4.7 Discussion: Interpretation on the Quantification of the Vehicle-Pedestrian Interaction

As the quantification of interaction samples demonstrates, the probability densities of the pedestrian early gaze and the late gaze were distinct in the yielding type scenarios. The early gaze tended to happen in the zone around 27 m for the V2P distance and around 12° for the absolute V2P angle, whereas the late gaze was more likely to take place in the zone around 12 m for the V2P distance and around 16° for the absolute V2P angle. These results reveal that there existed evident behavioral patterns of the pedestrian gazes as a function of V2P distance and V2P angle in the interactions where the vehicle yielded to the pedestrian around the crosswalk. For the early gaze which occurred at a relatively bigger V2P distance and a smaller V2P angle, it can be assumed that the pedestrian used it to make a primary visual exploration of the vehicle status and intention. Provided that the vehicle status and intention were still ambiguous for the pedestrian after this exploration, a secondary trial, namely the late gaze, would happen subsequently when the V2P distance became smaller and the V2P angle became bigger. The employment of the late gaze means to explore again the vehicle status and intention. This interpretation on the results of quantification is coherent with our previous review on the

vehicle-pedestrian samples in which the pedestrian carried out the gaze behavior twice when encountering the vehicle.

Moreover, it is notable that in the zone where the pedestrian early gaze tended to happen, there was nearly no vehicle slowing-down. Instead, the zone where the pedestrian late gaze had a higher probability to occur is superposed to a certain extent with the zone where the vehicle slowing-down had a higher probability to occur in terms of V2P distance and V2P angle. This superposition can be recognized in both distribution and probability density of the significant vehicle and pedestrian behaviors. This finding may reflect the fact that the vehicle yielding intention demonstrated by the vehicle slowing-down behavior was caught by the pedestrian just in time through the late gaze. As interpreted in the review of the interaction samples, the gaze is an indispensable behavior for pedestrians to look for information about the vehicle in the vehicle-pedestrian interaction. The slowing-down behavior is a perceivable signal for vehicles to demonstrate the yielding intention. When these two behaviors were in alignment with each other in terms of V2P distance and V2P angle, it can be deduced that a smooth communication of vehicle yielding intention was realized between the vehicle and the pedestrian. In retrospect, the pedestrian early gaze was not in alignment with the vehicle slowing-down in terms of V2P distance and V2P angle. This may reflect that the pedestrian only perceived an approaching vehicle from a long distance. Then, the pedestrian carried out the late gaze and it was in alignment with the vehicle slowing-down in terms of V2P distance and V2P angle. This may mean that the pedestrian caught the signal of yielding intention demonstrated by the vehicle slowing-down at this time. Hence, a communication of vehicle yielding intention was constituted between the vehicle and the pedestrian.

As regards the results about the non-yielding type scenarios, it is noticed that most of the pedestrians only carried out the late gaze towards the vehicle in their interaction. The reason can be that the pedestrian was able to make a firm crossing decision with this single gaze. However, no evident behavioral pattern for the late gaze was found in the non-yielding type scenarios. In order to interpret how the late gaze works in the interaction where the vehicle did not yield not the pedestrian, we attempted to divide the zone where the late gaze took place to three different parts. In the zone where the late gaze took place with a V2P distance being bigger than 20m and an absolute V2P angle being smaller than 15° , it can be assumed that the information about the vehicle perceived by the late gaze was that an approaching vehicle was still far away. With this information being already adequate, the pedestrian can determine that the gap between them and the vehicle was acceptable for achieving a road-crossing task prior to the vehicle. Hence, the pedestrian passed through the crosswalk, then the vehicle passed through the crosswalk. Based on this assumption, the interaction samples in this zone correspond actually to the observed scenario #5. Moreover, in the zone where the late gaze took place with a V2P distance being smaller than 10m and an absolute V2P angle being bigger than 30° , it can be assumed that the pedestrian visually perceived that the vehicle was already close to them. This information for the pedestrian meant that the road-crossing prior to the vehicle is dangerous. Therefore, the pedestrian would let the vehicle pass through the crosswalk in priority. Accordingly, the interaction samples in this zone correspond to what is observed in the scenario #6. In the zone where the late gaze took place with a V2P distance from 10 to 20 m and an absolute from 15° - 30° , it looks like the perceived information about the position of the pedestrian relative to the vehicle was not clear enough for the pedestrian to decide whether crossing the road prior to the vehicle or after the vehicle. Unlike the yielding-type scenarios in which the vehicle slowing-down happening in the same zone acted as a perceivable signal of

the yielding intention can help the pedestrian to make the crossing decision, the pedestrians in the non-yielding type scenarios would need to wait at the curb for ensuring safety. Therefore, the interaction samples in this zone correspond to the scenario #7 where the pedestrian waited for the vehicle which should have yielded to them.

4.8 Summary and Recommendations

In this section, we summarized the key findings and the related interpretations with regard to the behaviors and the communications in the vehicle-pedestrian interaction. Based on them, we draw some recommendations on the employment strategy of extended signals for AV2P communication functions.

From our review of the vehicle-pedestrian interaction samples:

- 8 basic and typical behaviors are recognized in the vehicle-pedestrian interaction around the unsignalized urban crosswalk, which are labeled as pedestrian walking, pedestrian gaze, pedestrian crossing, pedestrian waiting, vehicle approaching, vehicle slowing-down, vehicle stopping, as well as vehicle keeping-driving.
- With respect to the different sequences of the vehicle and pedestrian behaviors, seven scenarios are categorized which describe the different ways of how the vehicle and the pedestrian interact with each other.
- On the side of pedestrians, it is observed that the gaze behavior was widely performed by pedestrians for preparing the road-crossing. It seems like pedestrians carried out this visual behavior in a spontaneous way, which can be attributed to its indispensability in looking for information about the vehicle status and intention. It can be considered that the pedestrian gaze acts as one side of the communication channel for the information exchange in the vehicle-pedestrian interaction.
- Moreover, it is observed in the interaction samples that the pedestrian gaze could happen once or twice. For the samples with twice gazes, it can be assumed that the information about the vehicle provided by a primary gaze might not be adequate for making a crossing decision. Thereby, a secondary gaze needed to be carried out in order to explore again the vehicle status and intention. For the samples with once gaze, it can be assumed that the information provided by a single gaze was sufficient for the pedestrian to confirm the crossing decision. For further analyzing the pedestrian gaze, we gave the more specific labels to this visual behavior. For the primary gaze and the secondary gaze in the samples with twice gazes, they were relabeled respectively as the early gaze and the late gaze. For the single gaze in the samples with once gaze, they were relabeled as the late gaze.
- On the other side of vehicles, it is noticed that the vehicle slowing-down had different effects on the pedestrian behaviors, i.e. waiting or crossing. This may be explained by the fact that the vehicle slowing-down acts as a perceivable “signal” which demonstrates the yielding intention. When the vehicle demonstrated this signal from a long distance to the pedestrian, the pedestrian was able to understand early that there was a far vehicle with a yielding intention. This understanding allowed the pedestrian to decide to cross the road without waiting at the curb for saving time. Conversely, when the vehicle demonstrated this signal from a close distance to the pedestrian, the pedestrian had to wait at the curb and look

for more information for ensuring a safe crossing decision. Considering the role of the vehicle slowing-down in demonstrating the yielding intention, this vehicle behavior can be regarded as one other side of the communication channel for the information exchange in the vehicle-pedestrian interaction.

From our quantification of vehicle-pedestrian interaction samples by calculating the position of the pedestrian relative to the vehicle at the time of the pedestrian early gaze, the pedestrian late gaze, and vehicle slowing-down:

- It is found that there were the evident behavioral patterns of the pedestrian early gaze, the pedestrian late gaze, and vehicle slowing-down as a function of V2P distance and absolute V2P angle in the scenarios where the vehicle yielded to the pedestrian. The pedestrian early gaze, the pedestrian late gaze, and vehicle slowing-down had higher probabilities to occur respectively in the zone around 27 m for the V2P distance and 12° for the absolute V2P angle, in the zone around 12 m for the V2P distance and 16° for the absolute V2P angle, and in the zone around 14 m for the V2P distance and 16° for the absolute V2P angle.
- Notably, it is found in the yielding type scenarios that there was a trend of superposition between the zone where the pedestrian late gaze had a higher probability to occur and the zone where the vehicle slowing-down had a higher probability to occur in terms of V2P distance and V2P angle. This may be explained by fact that the vehicle slowing-down was caught just in time by the pedestrian late gaze. Since the indispensable role of the pedestrian gaze is to look for information about the vehicle and the vehicle slowing-down acts as a perceivable signal which demonstrates the yielding intention, it can be considered that a smooth communication of the vehicle yielding intention was constituted by the alignment between the vehicle slowing-down and the pedestrian late gaze.
- In the non-yielding type scenarios, no evident behavioral pattern of the pedestrian late gaze was found.

For the question of developing effective AV2P communication functions which consists of when to activate and where to place extended signals, the solution could be that they communicate AV intentions at the time when the pedestrian employs the gaze behavior and in the place where the pedestrian gaze fixate. The above employment strategy is recommended with the intention of adapting extended signals to the behavioral pattern of the pedestrian gaze. As the results of our quantification demonstrate, there existed the evident behavioral patterns of the pedestrian early gaze and the late gaze as a function of V2P distance and V2P angle in the yielding type scenarios. The superposition between the pedestrian late gaze and the vehicle slowing-down was observed, which can be interpreted by the fact that a smooth communication of the yielding intention was constituted by the alignment between the pedestrian gaze which works on looking for information about the vehicle and the vehicle slowing-down which acts as a perceivable signal of the yielding intention. Inspired by this assumed mechanism of alignment, it would be ideal that extended signals as a new explicit source of communicating the AV status and intention are employed by aligning with the behavioral pattern of the pedestrian gaze in order to allow the pedestrian to perceive and understand the AV status and intention in an expected way.

With respect to this recommendation, the activation timing of extended signals should be consistent with the zone where the gaze has a higher probability to take place (see Fig. 4.15). As regards the two recognized gazes, labeled as early and late gaze, the extended signal could

be activated two times depending on the requirement for communications. The first activation timing should be consistent with the zone where the early gaze has a higher probability to take place (V2P distance ≈ 27 m, absolute V2P angle $\approx 12^\circ$). Then, the second activation timing should be consistent with the zone where the late gaze has a higher probability to take place (V2P distance ≈ 12 m, absolute V2P angle $\approx 16^\circ$).

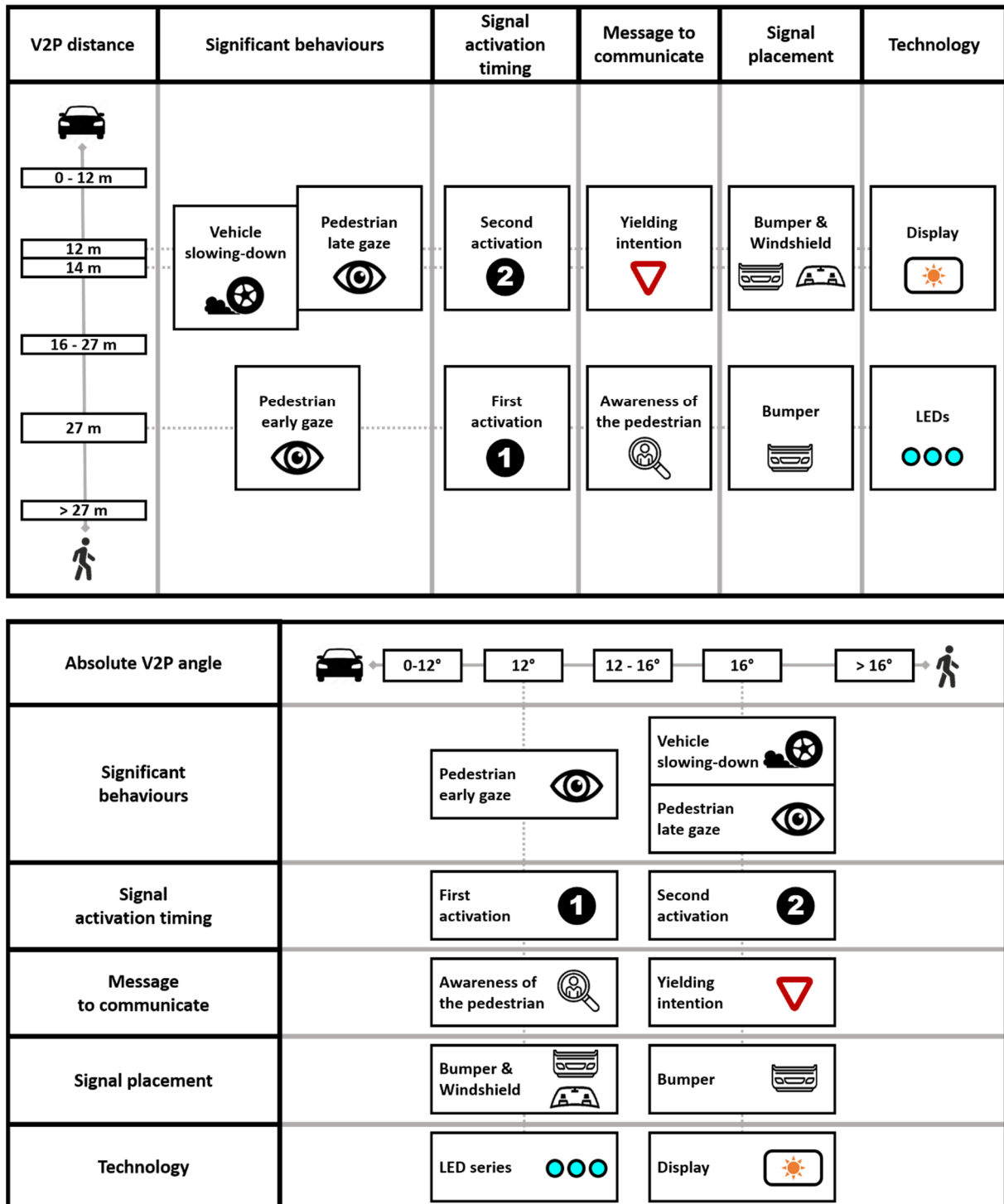


Fig. 4.15 Recommended employment strategy of extended signals for AV2P communication functions, in terms of activation timing, message to communicate, placement, and technology.

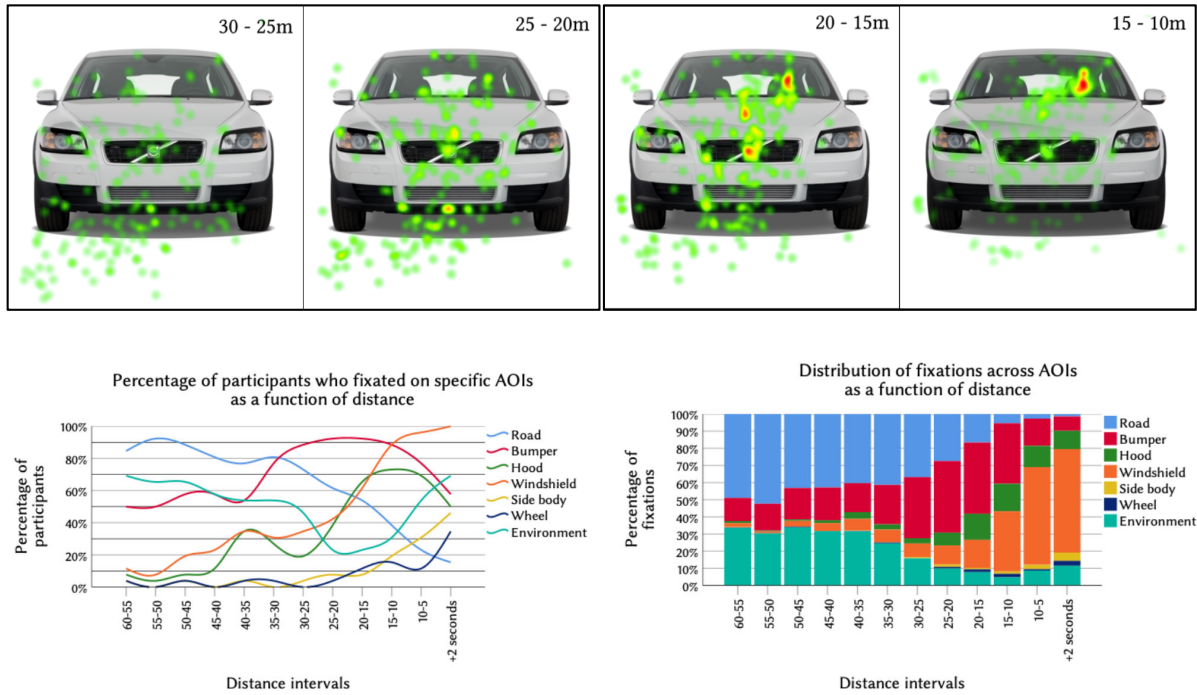


Fig. 4.16 Fixation pattern of the pedestrian gaze in the vehicle-pedestrian interaction studied by D. Dey *et al.* [136].

Regarding where the extended signal should be placed, the knowledge of the areas on which the pedestrian gaze fixates would be useful for suggesting a reasonable scheme. Referring to D. Dey *et al.* [136], their study addressing the fixation pattern of the pedestrian gaze in the vehicle-pedestrian interaction provided the information about the major areas fixated by the pedestrian gaze as a function of distance interval between the vehicle and the pedestrian (see Fig. 4.16). By combining their findings with our results on the zone where the gaze behavior had a higher probability to take place in terms of V2P distance, we can deduce the areas of interest to place extended signals. Accordingly, it is found that in the zone where the early gaze had a higher probability to take place (V2P distance ≈ 27 m, absolute V2P angle $\approx 12^\circ$), the major areas fixated on by the pedestrian gaze are the vehicle bumper and the road in front of the vehicle. In the position where the late gaze had a higher probability to take place (while V2P distance ≈ 12 m, absolute V2P angle $\approx 16^\circ$), the major areas fixated on by pedestrian gaze are the vehicle bumper and the vehicle windshield. It is therefore recommended that the vehicle windshield, the vehicle bumper, and the road in front of the vehicle should be of interest to place extended signals.

For the messages to be communicated, the AV awareness of the pedestrian and the yielding intention were discussed to be necessary for the AV-pedestrian interaction [49][82][89][106]. Considering the sequence of the pedestrian early and late gazes, the awareness of the pedestrian could be communicated by AVs in correspondence with the early gaze and the yielding intention could be communicated in correspondence with the late gaze.

To achieve AV2P communications through the appropriate technologies, LED arrays, displays, and light projection are three available options. According to the results on the distribution of the pedestrian early and late gazes, the usage of display and light projection which are limited in terms of display size and projection distance would probably not adapt to the early gaze

occurring far from the vehicle. On the contrary, the optical features of LED arrays could reach the requirement for a long-distance light communication. In the condition of a close-distance light communication, the display and light projection become available for the late gaze. However, as the above fixation pattern of the pedestrian gaze demonstrates, pedestrians have no habit to fixate on the road at a close distance to the vehicle [136]. In order to adapt to pedestrians, the light projection which projects extended signals on the road in front of the vehicle should be excluded from the technologies of interest for a close-distance light communication.

4.9 Limitations

The findings on how the pedestrian interacts with the vehicle around the urban crosswalk and on the related communication mechanism were discussed in this study. They contribute to drawing our primary recommendations on the employment strategy of extended signals for AV2P communication functions. Nonetheless, some limitations still need to be pointed out. As mentioned in the introduction of the method, an inevitable limitation of the observation study is that biases may exist in the analysis of the obtained results with a qualitative approach. This is because the researchers may subjectively misinterpret the observed road users' behaviors and the motive lying behind them [36]. In order to remedy this shortcoming as much as possible, we attempted to widely exchange, query, and discuss the assumed interpretations within the whole research team until reaching a common consistency.

In this study on the vehicle-pedestrian interaction, our scope is fixed on recognizing the vehicle and pedestrian behaviors, then analyzing their roles, effects, and cooperation in constituting a communication of information. Still, on the topic of vehicle-pedestrian interaction, the exploration should not be limited within only the behavior and the communication. According to existing research works, there are many other factors which can influence the way of how vehicles and pedestrians interact with each other, including culture, social norms, demographics, and traffic experience [36]. A comprehensive understanding of the vehicle-pedestrian interaction would require to take account of them. To study the above influencing factors which cannot be visually observed, a complement with surveys and interviews will be needed for updating an observation study. Nonetheless, with the purpose of proposing suitable employment strategy of extended signals, our particular attention to the constitution of a communication between the vehicle and the pedestrian seems to be reasonable and well oriented.

Another weakness existing in this study is that the number of exploitable samples for our proposed quantification of the vehicle-pedestrian interaction is still limited. Although a notable superposition of the probability density between the pedestrian gaze and the vehicle slowing-down was found and the spatial-temporal distribution of these behaviors are generally in line with what was observed in the review of the interaction samples, a more reliable argument would require more available samples to support.

4.10 Conclusion

AV2P light communication functions mean to clarify the AV status and intention through extended signals, which are expected to facilitate traffic interactions with pedestrians. For the successful implementation of these new functions into future shared road space, their effectiveness should be ensured. However, several existing research works on AV2P communication functions show that not all of them were regarded as reliable to ease the interaction with the vehicle from the point of view of the pedestrian [28][84][137]. This unexpected failure of AV2P communication functions is probably a result of the unsuitable employment of extended signals which does not adapt to pedestrians' communication habits in time and in place. In addition, it is observed that a large part of practical concepts of extended signals developed in the early stage treated the AV interaction problems with the pedestrian as dealing with an immobilized object in a scripted scenario, rather than a human being with variable behaviors in real traffic. All of these identified problems reveal that AV2P communication functions through extended signals still need to be evolved for better adapting to the pedestrian. Regarding the question of developing AV2P communication functions which consists of when to activate and where to place extended signals, it looks like the key to respond to this question stands in finding the suitable employment strategy that can adapt to the pedestrian. This consideration is properly under the principle of developing a user-centered HMI system. Hence, as pedestrians highly rely on the basic communications in present interactions with vehicles and no evidence has proven that they will be rejected in future interactions with AVs, close observations on today's vehicle-pedestrian interactions with particular attention to how information was communicated between vehicles and pedestrians would be helpful for recommending the reasonable employment strategy of extended signals. With this study direction, we investigated intentionally the vehicle-pedestrian interaction in the case of the unsignalized urban crosswalk by a naturalistic field observation supported with video recording. In the two selected observation sites situated in Paris, many hours of video footage were recorded and they were split into short clips which contain the pedestrian crossing scenes. For the video clips in which both the vehicle and the pedestrian are presented at the same time within the defined observation extent, they were considered as the vehicle-pedestrian interaction samples for the further review and quantification. The review of the vehicle-pedestrian interaction samples aims at providing the available materials which take note of what happened throughout the whole process of the vehicle-pedestrian interaction around the crosswalk. They were used to support a qualitative analysis on the motive lying behind the observed behaviors and the communications between the vehicle and the pedestrian. For the quantification of the vehicle-pedestrian interaction, we proposed to calculate the position of the pedestrian relative to the vehicle at the time of vehicle or pedestrian behaviors in terms of V2P distance and V2P angle. This was relied on to analyze the vehicle and pedestrian behavioral patterns. As a result of our review, seven scenarios of the vehicle-pedestrian interaction were distinguished with respect to the different behavioral sequences constituted of the eight recognized behaviors. Regarding them, it is observed that pedestrians usually carried out once or twice the gaze behavior towards the approaching vehicle while preparing the road-crossing. This can be attributed to the role of the gaze behavior in looking for information about the vehicle, which is indispensable for pedestrians to make crossing decision. Besides, the different effects of the vehicle slowing-down behavior on the pedestrian waiting or crossing behavior were noticed. This can be explained by the fact that the vehicle slowing-down acts as

a perceivable signal which demonstrates the yielding intention. When the vehicle demonstrated this signal from a long distance to the pedestrian, the pedestrian tended to cross the road without waiting at the curb. Conversely, when the vehicle demonstrated this signal from a close distance to the pedestrian, the pedestrian preferred to wait at the curb. Besides, the results of our quantification show that there existed the evident behavioral patterns of the pedestrian early gaze, the pedestrian late gaze, and the vehicle slowing-down as a function of V2P distance and absolute V2P angle in the scenarios where the vehicle yielded to the pedestrian. Notably, a trend of superposition in terms of V2P distance and absolute V2P angle was found between the zone where the pedestrian late gaze had a higher probability to occur and that of the vehicle slowing-down. This superposition can be interpreted by the fact that the vehicle slowing-down which demonstrated the yielding intention was caught just in time by the pedestrian late gaze which looked for information about the vehicle. It can be considered that a smooth communication of the vehicle yielding intention was constituted by the alignment between the vehicle slowing-down and the pedestrian gaze. Inspired by this insight on the constitution of a communication, we recommended that extended signals for AV2P communication functions which act as an explicit source of communicating the AV status and intention should be activated and placed by aligning with the behavioral pattern of the pedestrian gaze which works on looking for information about the vehicle. This recommended employment strategy which adapts to the pedestrian is expected to effectively facilitate the interaction between AVs and pedestrians. More specifically, the extended signals could be activated two times which are respectively consistent with the zones where the early and late gazes have higher probabilities to take place. Based on the fixation pattern of the pedestrian gaze in the vehicle-pedestrian interaction [136], the areas of interest to place the extended signals are found to be situated on the vehicle bumper and windshield. Overall, the main contribution of this study is that it provides more details about the different ways in which the pedestrian and the vehicle interact with each other around the urban crosswalk. Especially, the roles of the significant behaviors, i.e. pedestrian gaze and vehicle slowing-down, were pointed out and the interpretation on their cooperation to constitute the communication of the yielding intention was suggested. Based on this interpretation, we creatively recommend a pedestrian-adapted strategy in terms of activation timing and placing position to employ extended signals for AV2P communication functions. This contributes to responding to the question about when to activate and where to place extended signals, which were still much less developed in this domain of AV2P communication. Notably, as the recommended activation timings were specified in terms of V2P distance and V2P angle, these quantified data are able to provide the available basis for defining the dimensions and the optical features of extended signals. This is essential for ensuring the visibility of extended signals in AV2P communications. Even though this study, as an honest trial on studying the vehicle-pedestrian interaction with particular attention to the communication mechanism, provides the valuable findings and recommendations, the limitations still exist. The misinterpretation which may exist in the observation, the non-studied factors which can influence road users' behaviors, as well as the limited number of samples for the quantification reflect that this study can be further completed. Also, apart from the case of the unsignalized urban crosswalk, there are other traffic cases in which AVs had to interact with their surrounding road users. Knowing that our proposed employment strategy adapting to the pedestrian is use-case dependent, what should be the employment strategies for the other traffic cases needs other specific research.

Chapter 5. Conclusion and Perspectives

5.1 Conclusion

Signal lights play an indispensable role in modern vehicles. Through “being seen” by road users, they communicate the messages of vehicles’ presence, position, size, moving intention, or direction which contribute to safe and efficient traffic interactions. Lately, the adoption of day running lights and sequential turn indicators on vehicles represent the typical developments of signal lights for road safety. Yet, the research and development on automotive signal lights never stop. Numbers of suggestions were made for them to increase visibility, communicate more useful information, automatically adapt to the environment, as well as have astonishing appearances. This is mainly attributed to the progress of LED light sources, fine optical control, as well as automatic control technologies. In this thesis defined to study, design, and realize an extended automotive signalization, we equally head to participate in the study of future automotive signals. As a widely opened thesis, it provides great liberty in the research content that we can imagine lots of new functions and forms for automotive signals. However, worries appear at the same time in terms of the direction of kicking off. Our initial state-of-the-art study which sums up the existing suggestions on updating automotive signals demonstrates that a large number of them, such as creating more colors to differentiate signal lights and using new light patterns to communicate different types of braking, were rejected. In spite of the good intentions of these suggestions, the reason for rejecting them is due to the lack of evidence which proves a true need for the suggested signalization. Besides, in the age of information explosion, the mode “the more the better” does not apply to automotive signals. The excess of signals will overweigh communications among road users, which rather complicates traffic interactions. These facts warn us that the research on extending signals is not as simple as wishful thinking of adding some signaling functions to a vehicle. Instead, it is the need for new signalization that points to a reasonable path to extend automotive signals. Therefore, finding the need for new signalization is the stepping stone to make the contributive research on the topic of extended automotive signals and it is the first study that we realized. To this end, the cues are found with regard to AVs.

The latest technological advancement brings advanced automatic functions into vehicles, which update continuously vehicles from partial automation to full automation. This will gradually release in-cabin humans from taking the role of drivers to passengers. Optimistically, the benefits of AVs in safety and comfort are claimed by markets. Still, since the driving, no matter manually or automatically, is anyhow a social activity, the AV interactions with other road users need to be considered for constructing smart cooperation in the future shared road space. Thereby, we made a deep state-of-the-art study with eyes on the AV interaction problems. Many research works point out that people had concerns about autonomous driving abilities and held a cautious disposition in the interaction with AVs. Besides, it is found that AVs and other road users behaved awkwardly with each other, as AVs had no means to explicitly express their intentions and other road users had no idea of what AVs intended to do. These interaction problems reveal a lack of communication for AVs to clarify their status and intentions. Notably,

as covered in the research works with respect to different road users, pedestrians were mostly involved in the interaction problems with AVs. This is because many conventional communications including eye contact, hand gesture, and facial expression between drivers and pedestrians will be cut off when drivers are no longer available in AVs. From these reviews, it can be argued that there is an AV requirement for the communication abilities with the purpose of facilitating their interactions with others and this requirement is especially true while interacting with pedestrians. Accordingly, academics, industries, and administrations suggested providing AVs with AV2P communication abilities. For this purpose, automotive signal lights show great potential to be extended for signaling the AV status and intentions. For decades, signal lights have been used in traffic as an important communication modality. The recent research works also reported that road users prefer to be notified about the AV by light signals. Most importantly, the tests on AV2P communication functions by showing extended signals have proven their benefits for safe, fast, and comfortable interactions. As regards this thesis, this is where the need for new signalization is found. Our review in this part of the study systematically shows the AV interaction problems and summarizes the cause consisting of the lack of communication. This leads us to a valuable research point of providing AV2P communication functions. There, the automotive signal lights can be expected to carry out the basic signalization and further extended to provide advanced communication functions. Nonetheless, in our next exploration of how AVs communicate to pedestrians through extended signals, the problematics are observed.

In few research works, contradictory findings were announced in terms of the effectiveness of AV2P communication functions which apply extended signals. Some communication functions did not achieve their promise of facilitating the interaction between AV and pedestrians as they were regarded to be partially trustworthy and unreliable. Based on our observation, such unexpected performance was likely due to the improper signal design and the unsuitable adaptation to pedestrians' basic communication habits. In this early development stage AV2P communication functions, big liberty is open for the design of extended signals including new light patterns, pictograms, and texts. Without the standards, academics and industries made their signal designs in all directions. Consequently, some improper signal designs might perform ineffectively as they are meaningless from the perspective of pedestrians. Besides, in vehicle-pedestrian interactions, pedestrians need to get useful vehicle information in time and in place for letting them make the decision in response to vehicles. A retard or a wrong place to show extended signals which does not adapt to pedestrians' communication habits might disturb pedestrians. Correspondingly, we consider that what are the appropriate signal designs for expressing AV information and how the extended signal should be activated and placed are two main questions that need to be responded for developing user-centered AV2P light communication functions. Therefore, it would be important to further evaluate the performance of extended signals in different forms and observe closely the vehicle-pedestrian interactions with particular attention to their communication mechanism. Our observation and analysis in this part reveal two questions about extended signals and proposed the research directions. With respect to them, we realized two independent studies, one for signal designs and the other one for activating timing and placing position of signals, in order to provide our recommendations on extended signals used for AV2P communications.

For the question related to signal designs, extended signals in the forms of light patterns, pictograms, and texts have been evaluated with a lot of criteria in many research works. These criteria involve the pedestrian crossing decision time, the perceived safety feeling, the personal

preference, and so on. However, we noticed that the studies on the understandability of extended signals are very limited. Essentially, the primary basis for the usability of extended signals is that the communications can be adapted in a well-understood manner. This suggests that particular studies on evaluating the understandability of extended signals are quite necessary. Therefore, we conducted a series of tests in an online interface to investigate how subjects can understand the extended signals. In this investigation, we focused on the light patterns and the pictograms which communicate the vehicle yielding intention in a vehicle-pedestrian encounter scenario around the crosswalk, as it is a typical interaction case involving AVs in the future and the clarity of right of way is important for traffic safety and efficiency. The light patterns were designed by differing in motion and color. The pictograms, which convey egocentric advice, state allocentric vehicle information, or combine both to constitute a notion of cooperation, were designed by differing in figure, symbol, and color. These signal designs allow us to study in a controlled manner the understandability depending on the signal form, the content type, and the composing elements. As a result, it is found that, as regards the light patterns, their inherent understandability was bad in terms of correctly expressing the yielding intention. In addition, none of the different motions and colors enabled promoting the interpretation correctness. Such performance of the light patterns suggests that they may not be a suitable signal form to convey complex messages for AV2P communication functions. One main barrier of using them lies in how to make pedestrians understand their given meaning, rather than proposing more new designs. For this, a learning phase would be highly required with the help of traffic administration. As regards the pictograms, they performed relatively well for expressing the yielding intention. This suggests that it would be better to rely on them to convey complex messages in AV2P communications. However, the diverse types of confusion were observed for the pictograms, due to the ambiguity of concerned traffic actor, the similarity to existing traffic signs, or the wrong interaction focus. This reflects one potential risk of using pictograms and such confusion needs to be overcome during the design process. Moreover, it is identified that the pictograms stating allocentric vehicle information were less interpretable than those conveying egocentric advice. The existence of actor figure and field figure can ease the understanding of the pictograms. For this investigation, its main contribution is providing the useful evidence for selecting the appropriate signal designs. Also, it yields the practical guidelines for designing the understandable signals, especially those in the aspects of composing elements and confusion. These contributions are meaningful for driving the standardization of extended signals used for AV2P communications.

For the question related to activation timing and placing position of signals, the discussion is in progress along with the development of AV2P communication concepts. It is noticed that most of these concepts deal with pedestrians as immobilized objects or in scripted interaction cases instead of human beings who can behave variously depending on the basic communication mechanism. Since pedestrians highly rely on the communications through implicit and behavioral channels to interact with vehicles. It would be preferable to take account of them for defining the employment strategy of extended signals in terms of timing and placing. For this purpose, close observations on day-to-day vehicle-pedestrian interactions with particular attention to how communications happen is needed to find useful cues. Therefore, we launched a naturalistic observation which focused on vehicle-pedestrian interactions around urban crosswalks. With the help of video recording, the interaction samples were collected for analyzing vehicle and pedestrian behaviors. We proposed a new perspective, that the vehicle-pedestrian interaction can be quantified as the position of the pedestrian relative to the vehicle

at the time of vehicle or pedestrian behaviors in terms of the V2P distance and angle, to further study the interaction sample with specific data. As a result, it is observed that the gaze behavior is indispensable for pedestrians to look for useful information in their interactions with vehicles. The slowing-down behavior for vehicles acts as a prominent signal to demonstrate their yielding intention. Furthermore, the quantification of vehicle-pedestrian interactions shows that there existed the evident behavioral patterns of pedestrian early gaze, pedestrian late gaze, and vehicle slowing-down as a function of V2P distance and angle in the scenarios where the vehicle yielded to the pedestrian. Notably, a trend of superposition was found between the zones where the pedestrian late gaze had a higher probability to occur and that of the vehicle slowing-down in terms of V2P distance and angle. This can be interpreted by the fact that the vehicle slowing down which demonstrates the yielding intention was caught just in time by the pedestrian late gaze which looks for vehicle information. It can be considered here that a smooth communication of vehicle yielding intention was constituted by the alignment between the vehicle slowing-down and the pedestrian gaze. Inspired by these insights, we recommend that the extended signals used to communicate AV intentions should be employed in alignment with the pedestrian gaze in order to achieve a pedestrian-adapted communication. Specifically, the activating timing of extended signals should be consistent with the zone where the pedestrian gazes have a higher probability to occur in terms of V2P distance and angle. The placing positions of extended signals should be the vehicle bumper and windshield based on the fixation pattern of pedestrian gaze. Overall, the contribution of this research is bringing a rational interpretation on how the communication was constituted by the vehicle and pedestrian behaviors, upon which recommendations on when and where to employ the extended signals can be drawn logically. Above that, the recommendations with the specific distances, angles, and positions are significant for further defining the optical features of extended signals.

As a new road user in the future, AVs mean a revolutionary change in vehicle usage by offering the opportunity for safety, efficiency, and accessibility. Not being limited only as a novel mobility system, AVs also stand for a novel approach to the human lifestyle. Still, the path to AVs is full of uncertainties. Their adoption requires not only the robust operation of in-vehicle technological enablers, but also the satisfactory ex-vehicle interactions with other road users. For having such interactions, providing AVs with communications abilities through new automotive signalization become a hot research point. As a thesis that aims at studying extended signals, we engaged in the discussion and bring honest contributions to this research point. By intentionally focusing on the vehicle-pedestrian interactions around the crosswalk, we realized one study on finding the appropriate signal designs and one study on defining the activating timing and placing position of extended signals. Our findings bring new insights on the understandability of signals in different forms and the communication mechanism between vehicles and pedestrians, which are essential to ensure the effectiveness of applying extended signals. It is expected that these insights can support car manufacturers to specify their advanced signal light systems and help standard developing organizations to unify the ways of developing extended signals. Yet, our studies are only small pieces of the puzzle. Research works are still lacking for composing fully-functional extended signals for AVs. This is especially true in the validation of proposed extended signals in the real world, as AVs have not been allowed into regular traffic. In this early stage of researching extended signals, the theoretical studies by taking account of influencing factors in the specific use cases and the prototyping by evaluating the hard engineering matters should be made as much as possible.

5.2 Perspectives

As a thesis to study, design, and realize an extended automotive signalization, we targeted the communication functions which express the AV status and intentions through extended signals. With the aim of ensuring the effectiveness of extended signals, two studies were realized in terms of signal design and communication mechanism. They actually respond to what the extended signals should be like, when, and where the extended signals should be employed. To the end of realizing an extended automotive signalization, there is still a question on how to implement the extended signals in practice. Otherwise, we mainly focused on the vehicle-pedestrian interaction around the urban crosswalk, as the first step to research the usage of extended signals. Facing a great variety of situations in traffic, there are evidently other use cases in which the extended signals would be required for providing safe, efficient, and comfortable interaction experiences with AVs. At the end of this thesis, we would like to talk about the extended signals in the aspects of their implementation in practice and their applications in other use cases by providing some basic information and proposing some valuable research points. We hope that they can contribute to guiding the following research works in valuable directions.

5.2.1 Implementation in practice

For implementing extended signals in the forms of light patterns, pictograms, and texts in practice, competent lighting, displaying, and projection technologies will be required. Presently, the *liquid crystal display (LCD)*, the OLED, the LED self-emission for imaging, the *digital light processing (DLP)*, and the *micro lens array (MLA)* shows great potential to be applied on vehicles for realizing the advanced communication functions. Each of them has its advantages and shortcomings, which need to be evaluated for the adoption.

Backlight LCD is a classic flat-panel display that uses liquid crystals in its primary form of operation [178]. As regards the working principle, a LCD, lit by a backlight, controls electronically the liquid crystals to rotate polarized lights in order to switching on/off the pixels. Then, for composing colored images, the lights passing through the liquid crystal layer need to be colorized by a RGB filter behind. In the last decades, this display technology is widely used in home TVs, instrument dashboards, and screens in public places. As a highly mature technology for high-resolution displays, using LCD to show pictograms and texts is a solution that can be easily imagined for providing vehicles with the low-cost and reliable communication functions (see Table 5.1).

Still, some shortcomings exist for LCDs. As the existence of liquid crystal layer, it is difficult to shape LCD in complex shapes. Additionally, for the LCD which uses incandescent or cold cathode fluorescent lamps as the backlight source, it is always space-occupying and energy-consuming. Presently, for improving this point, LCDs have been updated by applying LEDs as the backlight, namely LED backlight LCD. This type of LCD can reduce well the thickness of the screen panel and save the consumption. Besides, the application of LED backlights prolongs the lifespan of LCDs effectively.

Table 5.1 Available technologies, signal forms, and product illustration for the AV2P communication functions



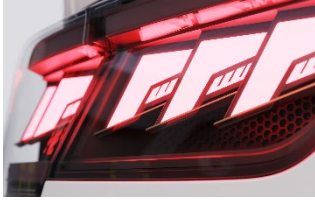







TECH.	Backlight LCD		OLED		LEDs self-emissive arrays for the display	
	Pictogram & Text		Pictogram & Text		Light pattern	
PRODUCT ILLUSTRATION	PLASTIC OMNIUM Rear combination light 		MARELLI AL Front display 		HELLA Flatlight μMX 	
	HASCO Intelligent signal display 		AUDI AI: ME Multi-purpose headlight 			
TECH.	LEDs self-emissive arrays with light guides		LEDs self-emissive arrays with the shelter		mLED self-emissive display	DMD-based DLP
SIGNAL FORM	Light pattern		Light pattern		Pictogram & Text	Pictogram & Text
PRODUCT ILLUSTRATION	HELLA Thick-walled edge light 		HELLA Radom 		MARELLI AL Dynamic interface 	
	OSRAM Digital projection system 		OSRAM Decorative light 			



Fig. 5.1 Electric vehicle LITE from BAIC Group equipped with the backlight LCD for the AV2P communication.

Besides, LCDs have one major limitation related to the propriety of liquid crystals. The liquid crystals cannot completely close to shade all lights emitted from the backlight. When a backlight is set to light up the entire LCD, there are always lights passing through the liquid crystals though they are closed for having the black pixels. As shown in Fig. 5.1, this makes the pixels on LCD be incapable of achieving a pure black but mostly a grey. Consequently, the contrast of LCD can hardly reach a top level (maximum: 4000:1) for attaining an excellent visual experience [179]. With regard to this issue of low contrast, the solution by the means of local dimming emerged with the support of tiny LEDs. In this solution, a large amount of tiny and arranged LEDs are applied as the backlight which is digitally divided into many small areas. For the areas which needs to display images, the corresponding groups of tiny LEDs are locally lit. For the other areas, these corresponding groups of tiny LEDs are deactivated. Following this principle, the local dimming instead of lighting up the entire backlight positively increases the contrast of displayed images on LCDs.

OLED is a very thin LED with organic layers deposited on a rigid or flexible transparent substrate [180]. Driven by a certain electric field, electrons and holes are injected from the cathode and the anode into the transport layer (ETL and HTL). They meet each other in the emitting material layer (EML). Their meeting recombines forming excitons that lead the emitting material to be self-luminescent (see Fig. 5.2). Relying on the important features that OLEDs can be multi-partitioned and the microscopic pixels on OLEDs can be independently controlled, an OLED module is able to flexibly display good-looking light patterns and pictograms. Hence, OLEDs consist of a practical display technology that enables vehicles to achieve the carmaker branding, the user-level personalization, and the information exchange between vehicles and other road users (see Table 5.1).

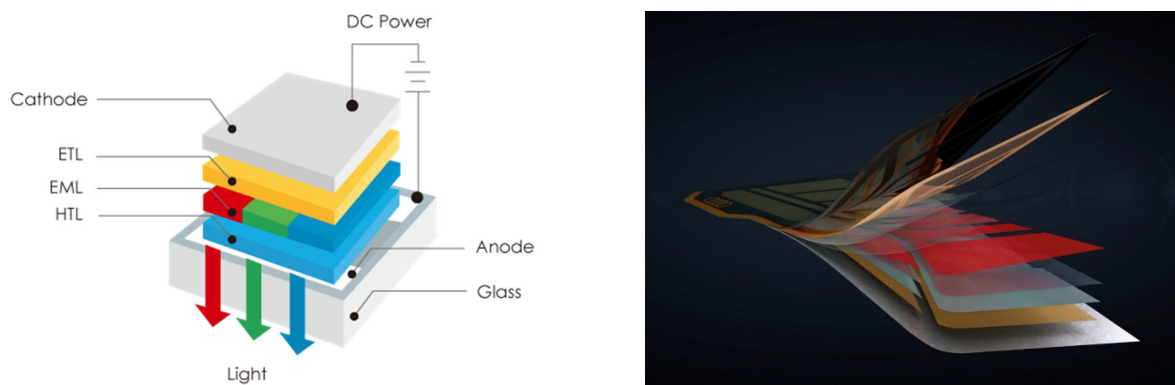


Fig. 5.2 Structure and working principle of the thin and flexible OLED.

Compared to LCDs with the backlight, OLEDs are a self-emissive display technology that can activate pixels for creating colored images or deactivate pixels for having the pure black. This allows OLEDs to have a perfect contrast (infinity in theory) performance for providing sharp and showy images. Also, deactivating the unneeded pixels during the image display can reduce the electricity consumption of a vehicle. Besides, OLEDs with a small number of composing layers enable a better light transmission and a wider viewing angle.

However, this promising display technology had the shortcomings as well. As mentioned in its name, OLEDs rely on organic materials, which are easy to become aging, to compose their emissive layers. If a certain area is used to display a high-luminance image for a long time, a “burn-in” image will permanently reside on the OLED. In the aspect of cost, the price of OLEDs is still not low enough for massively adopting them on automotive internal and external displays.

LED self-emission for imaging, being different from using LEDs as the backlight, relies on LED arrays with each LED functioning directly as the basic pixels. In early days, the arrays composed of big-dimension and monochrome LEDs haven been widely used in advertising panels, which can display simple texts and low-quality images. Nowadays, by further miniaturizing and individually controlling LEDs, LED self-emissive arrays for the display are able to demonstrate precise and complex images constituted of small pixels, even in the microscopic dimension. By creatively attaching LED arrays to the vehicle body, a variety of solutions can be developed for providing vehicles with bright light communication functions (see Table 5.1).

Nevertheless, regarding LED arrays with each LED in the millimetric scale, their usage for displaying pictograms or texts still has blemishes. As shown in the HASCO intelligent signal display, the halos caused by the light leakage of high-luminance LEDs lead the demonstrated contents to be blurry. To clear up this unsightly effect and improve the image clarity, the isolation for the light diffusion by the means of specific optical designs is required. Apart from this, another method for avoiding the halo effect is to have accurate dimming functions based on a big number of miniaturized LEDs. Currently, the *mini LED (mLED)* display features the RGB LED arrays in the same panel, with each LED measured in 100-300 μm [181]. This advanced technology is able to have image displays with high resolutions and a wide color gamut. Furthermore, the *micro LED (μLED)* display is being developed to reduce the dimension of LED to $<100 \mu\text{m}$. This inorganic display technology is expected to replace the OLED in the

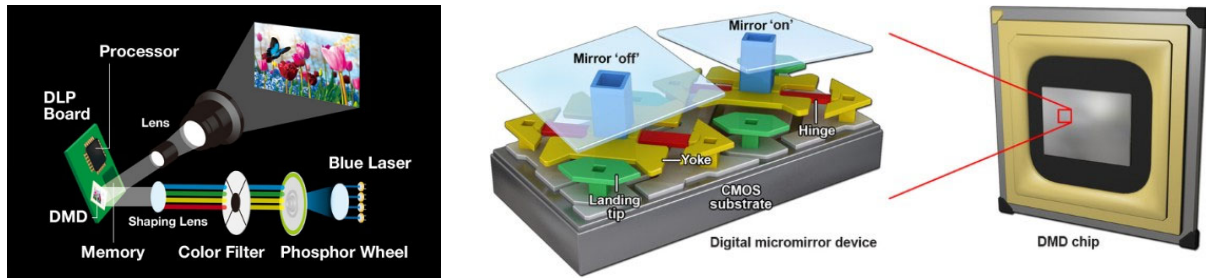


Fig. 5.3 Structure and working principle of the DMD-based DLP.

future on account of its advantages of higher brightness and longer lifespan. However, the μ LEDs still face a lot of technological challenges which limit its massive production in the aspects of epitaxial growth, mass transfer, and package test.

Moreover, other variants based on LED self-emission are developed to show homogenous and dynamic light patterns for light communication functions, for example, the controllable LED arrays associated with light guides or multi-aperture shelters (see Table 5.1).

DLP is an advanced technology for light projection by controlling the *digital micro-mirror device (DMD)* [182]. As the core of this technology, the DMD is composed of a large number of high-speed switchable micro reflective mirrors which are integrated into a small chip. According to the digital inputs which represent the desired light distribution, the rotation and the stopping time of each micro-mirror on the DMD are fixed for having the specific angles of light reflection (see Fig. 5.3). Reflected by the DMD, the lights pass through the projection lens and constitute high-resolution images. Compared to the current adaptive driving beam which controls a certain number of LEDs, the DMD-based DLP can realize the illumination and the image projection at the level of million pixels. With the purpose of achieving the light communication functions, this technology can be used to project the dynamic and precise pictograms or texts on the road surface which makes the automotive signalization no longer being limited within the vehicle body (see Table 5.1).

MLA is a set of precisely fabricated micrometer-sized lenses [183][184]. By adding an LED light source and a collimator, a typical MLA-based projection assembly is constituted. About its working principle (see Fig. 5.4), the light emitted from the LED source (1) firstly passes through a total reflection collimator (2). This collimating lens works on minimizing the light loss and guiding the light uniformly into the MLA (3). Arriving at the MLA, the incident light is converged to the focal plane where the shading interlayer (4) is situated. On the shading layer, there are lots of micro openings whose role is to shape the defined light and dark distribution. After that, the shaped light distribution passing through the projection layer (5) is projected on an objective surface. In the MLA, each micro lens works as an optical projection unit. By arranging these micro lenses horizontally and vertically, each shaped light distribution is projected and superimposed on the objective surface, thus resulting in a sharply focused image. Compared to the DLP projector which still necessitates a long minimum distance between the light source and the projection lens, the MLA projector has a greatly reduced focal length. This leads to a much small depth (30-50 mm) and a big projected flux for the MLA projector. Thanks to its small dimension, the MLA can be regarded as a flexible way to realize the light communication functions by projecting images on the road surface. Besides, one of its other

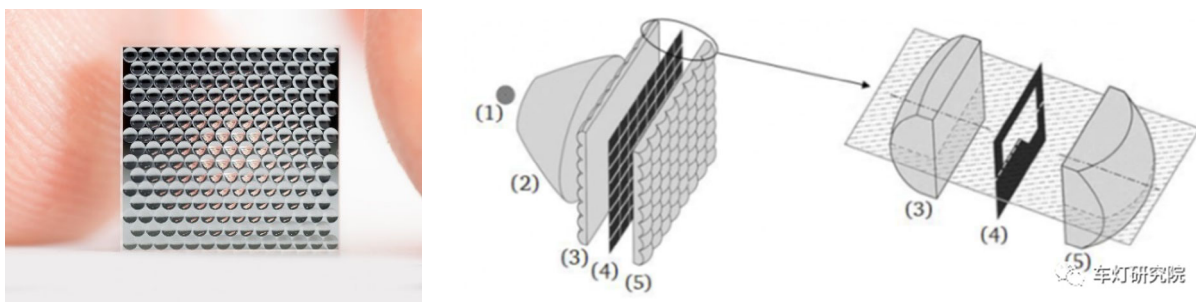


Fig. 5.4 Structure and working principle of the MLA projection.

advantage is that its objective surface can be flat, curved, or tilted. However, the MLA projector can only project a single image defined in the shading layer, which cannot be digitally controlled.

Apart from verifying the capability of showing extended signals, there are other matters, especially in the aspect of the vehicle engineering that must be considered for implementing light communication functions into practice. For each technology to show extended signals, the system integration into the vehicle, the influence on the vehicle style, the protection of the applied devices, their lifespan, etc. need to be carefully evaluated.

As regards the LCD and the mLED self-emissive display, these two typical flat-panel displays need to open or reserve slots on the vehicle body for the installation. This may bring a big impact to the vehicle structure that will not be easily accepted. Even though the radiator grille will be no longer needed on electric vehicles which can be used for light communication functions, the other important systems, for example, Radar and Lidar, are also waiting for occupying this valuable space. From this point, it should be supposed that the arrangement among the LCD and the mLED display for light communication functions and the other vehicle systems need to be further developed. In addition, the form of flat-panel LCDs and mLED displays may be conflict with the complex form of vehicle body. This does not leave a great room for the designers of vehicle style. Comparatively, the thin and flexible OLEDs are easier to replace and update the classic signal lamps situated in the vehicle concerns, which shows new signals to communicate safety or comfort-related messages. Moreover, the flexible and partitionable OLEDs are friendly for the design of vehicle style. As regards the solution based on the LED self-emission, the installation of LED arrays to show light patterns can well adapt to the lines of vehicle body, and that to show pictograms or texts can be attached to the curved surface of vehicle body. This lighting technology is likely to extend the present automotive signal lights and pose less problems on affecting the vehicle structure. In addition, the design liberty is widely open for using LED arrays to decorate the vehicle exterior, which leads style designers to make their vehicle brands unique and differentiable. Regarding the DMD-based DLP, the projection of dynamic pictograms or texts can be achieved by controlling the microscopic DMD chip. However, the other indispensable components, including light source, lens, and color filter, make a DLP projector space-occupying. In today's high-end vehicles, the DLP projector gradually takes the place of the LED-matrix headlamp, which takes over the adaptive driving beam function to illustrate the road in front of the vehicle and maybe provides the road projection function in the future. It can also be supposed that this projector can be swimmingly integrated into the vehicle back by sharing the space with the rear light assembly.

However, for realizing the road projection on the two sides of a vehicle, there seems to not exist a deep space for the installation of the DLP projector. As regards using the MLA to project pictograms, its small optical structure determines that it can be easily implanted and hidden on any part of a vehicle, such as chassis, bumper, or rearview mirror. This will not touch the vehicle structure and style a lot.

Furthermore, the installation of the new lighting, display, or the projection devices on a vehicle should take account of the related protection and dedust. The LCDs and mLED displays are fragile with regard to the collision and the scratch, which will bring the anxiety to vehicle owners. Moreover, the functionality of projection devices may be degraded or totally lost due to the dust or the sludge. This happens especially in the cases where the projection devices are installed at a low level of a vehicle, for example, a MLA on the vehicle chassis for projecting a welcoming message.

About the lifespan under the present technological context, the applications of LCDs, OLEDs, and mLED displays can last around 30-50K, 20-30K, and 80-100K hours respectively [185].

Table 5.2 Summary of the capacity and the restriction of the available technologies for achieving the light communication functions

Capacity	Technology	Restriction
Low cost and reliable display adapting to a wide range of use cases for showing vehicle status and intentions	LCD	Need to reserve big space for the installation; Arrangement with other automotive systems, Conflict with the vehicle shape; Protection.
Flexible display to replace and update the classic signal lamps for providing good-looking extended signals	OLED	Shorter lifespan due to the burn in; Not enough low cost
Long visual distance, free-to-design lighting solution to show light patterns, pictograms, and texts.	LED self-emssion arrays	Need for additional light guide, shelder, or other optic designs to ensure the good optical perfomance
High visual-experience display adapting to a wide range of use cases	mLED display	Need to reserve big space for the installation; Arrangement with other automotive systems, Conflict with the vehicle shape; Protection; High cost
Extend automotive signals from being seen on the vehicle body to the near road surface for welcoming navigating, and guiding through high-resolution pictograms and texts	DMD-based DLP	Space-occupying; Dedust
	MLA projection	Dedust

Some caution is needed for OLEDs, which will start to get “burnt in” images from 30K hours’ continuous application. To resolve it, the automatic care functions by adjusting the luminance and refreshing the pixels should be added to OLED applications. As regards the LED self-emissive arrays, the DLP projector, and the MLA projector, their lifespans mostly depend on the light source. In the case where the industrial grade LEDs are used, it can be assumed that their lifespan will last to around 50-100K hours. For handling the role in showing extended signals on a vehicle, the lifespan of the above-mentioned devices is acceptable.

Presently, the rapid development of lighting, display, and projection technologies provides ubiquitous HMIs around us. According to our review of these technologies, it is concluded that there is no insurmountable technological obstacle in terms of showing the extended signals to road users. The available lighting, display, and projection technologies are fully capable of demonstrating light patterns, pictograms, and texts on the vehicle body and on the road surface for signaling the vehicle status, intentions, or other information in need (see Table 5.2). Certainly, some shortcomings in terms of optical performance still need to be further improved. Nonetheless, it is in some cases the engineering matters that gravely restrict landing the related technologies on vehicles. Throughout history, the vehicle evolution was conducted in small steps by gradually extending and replacing existing organs. Adding a totally new and influencing thing into vehicles is full of risk from the perspective of vehicle engineers. Hence, engineering matters must be carefully considered in order to ensuring that the technologies can be feasibly adopted on vehicles. To do so, we have initiated a simple evaluation on the available technologies for light communication functions in terms of the system integration, the impact on vehicle style, the protection, the dust, and the lifespan. Still, this evaluation should be further developed and other engineering matters should be involved, for example, energy consumption, anti-vibration, head dissipation, and connection with the electronic unit. In the next steps, a deeper study on the topic of vehicle engineering is recommended with the purpose of illustrating possible restrictions, proposing related solutions, and making necessary tradeoffs with respect to each alternative technology for light communication functions.

5.2.1 Applications in other use cases

As regards lots of promising AV applications in the future, there are other use cases in which extended signals would be beneficial for safe, efficient, and comfort interaction between AVs and other road users, for example, vehicle automatic parking/departing in parking lots, customer picking-up/dropping-off by rental robot cars or driverless buses, operation of unmanned working machines, and unmanned delivery by AVs. These cases open new research themes on the usage of extended signals and each of them deserved to be delicately studied. For letting the extended signals effectively work in these use cases, it is recommended that the studies on the understandability of signal designs and the users’ communication mechanism should be similarly carried out as what we did for the vehicle-pedestrian interaction case around the crosswalk.

Automatic parking/departing in parking lots represent a low-speed scenario for the early autonomous driving application where there are less traffic regulations. Road users in parking lots including pedestrians and other drivers may face the danger of collisions when the AV turning or reversing intention is not clear due to the visual occlusion of other vehicles or walls

(see Fig. 5.5a). In this scenario, the projection of extended signals which represent the vehicle turning and reserving intention would be beneficial for pedestrians to avoid the potential danger. Nevertheless, this signal projected on the road is hard to be perceived by other in-cabin drivers who are also turning or reversing their vehicles, as their view habitually cannot reach the ground. Hence, other extended signals, for example, a red blinking light around the vehicle for achieving a 360° signalization would be of interest for the surrounding in-cabin drivers to get the information about the existence of a turning or reserving AV. Here, the study on the pedestrian gaze and in-cabin driver gaze behaviors while facing the scene of parking lots should be respectively studied with the purpose of proposing the right placing position of extended signals. Also, the study on road users' understanding of road markings and wall markings in parking lots would be useful for proposing the signal designs adapting to parking lots.

Customer picking up/dropping-off by rental robot cars or driverless buses is two important scenarios in future AV-sharing services (see Fig. 5.5b). As regards renting an AV also as known as a robot car, the traditional picking-up mode that “I search for the car” will be replaced by “the car searches for me”. In the scenario where an AV searches for customers and comes close to the picking-up point, it can be supposed that the AV awareness of customers, the marking of command reference, as well as the welcoming could be communicated with the help of new automotive signals for providing customers with the convenience and comfort. Subsequently, the notification of stopping position and the door opening warning demonstrated by road projection would be valuable in the safety aspect. In the dropping-off scenario, the exiting direction by a rear display or road projection could be an addition for protecting customers from accidents with vehicles in the back. In fact, the pick-up and dropping-off scenarios in urban areas are complex for rental robot cars, which contain diverse factors that need to be studied for developing light communication functions. The studies should attentively take account of the customers' behavior, i.e. visual checking, opening-door, and entering/exiting-car, the surrounding vehicles' behaviors, i.e. overtaking and waiting, the road environments of different types of picking-up points, i.e. around the residences, around the school, as well as the restriction from current traffic regulations. Moreover, the study on the signal designs needs to consider how to ensure the understandability and avoid the signal overweight. Being similar to rental robot cars, driverless buses can also rely on extended signals to facilitate their interactions



(a)



(b)

Fig. 5.5 Automatic parking/departing scenario in parking lots (a) and picking-up scenario in the AV-sharing service

with passengers, for example, enter/exit instructions and guidelines. The major differences between driverless buses and rental robot cars are that the picking-up and dropping-off scenarios for driverless buses are less complex. This is because the environment of bus stations is stable, in which passengers have the behaviors in order. Hence, the studies on passengers' behavioral habits and the adaptive solutions to employ extended signals are likely to be realized with less difficulties. Still, as unmanned buses generally aim at multiple passengers, the signal designs should cover a group of people and enable a unified understanding.

Operation of unmanned working machines, such as autonomous forklifts and tractors, represents the applications that combine AVs and operational machines. It can be imagined that these applications will be seen soon in industrial working sites for reducing labor costs and improving production efficiency. In the scenarios where unmanned working machines and other humans work in the same place, the indication of the machine status and the notification of the prohibited zone would be highly required with the purpose of improving safety (see Fig. 5.6a). The communication of the machine's working paths and negotiation of passage priority would be necessary for improving working efficiency. Ideally, extended signals, such as conspicuous blinks and marking projection, own great potential to fulfill these requirements. To develop extended signals for these unmanned working machines, the study should regard the characters of industrial sites and the specific behaviors of human workers. Besides, since there are already a large number of warning signs in industrial sites, the study on the signal designs should attempt to reach a consistent style with the existing signs and avoid excessive complexity for the understanding.

Unmanned delivery consists of a very useful and promising AV application. Especially, the public health crisis caused by Covid-19 emphasizes the need for this application to reduce the contact among people during the special period. For the unmanned delivery, it involves a key scenario that is handing packages to recipients. In this scenario, the comfort interaction experiences would be a value-added point for delivery companies. To this point, the communications between delivery AVs and recipients through extended automotive signals are likely to made contributions. Currently, it can be seen that some big delivery companies have already equipped their delivery AVs with eHMIs for identifying recipients and communicating command references (see Fig. 5.6b). Nevertheless, more comfort and safe interaction experiences can be provided by communicating the welcome message, the appreciation, and

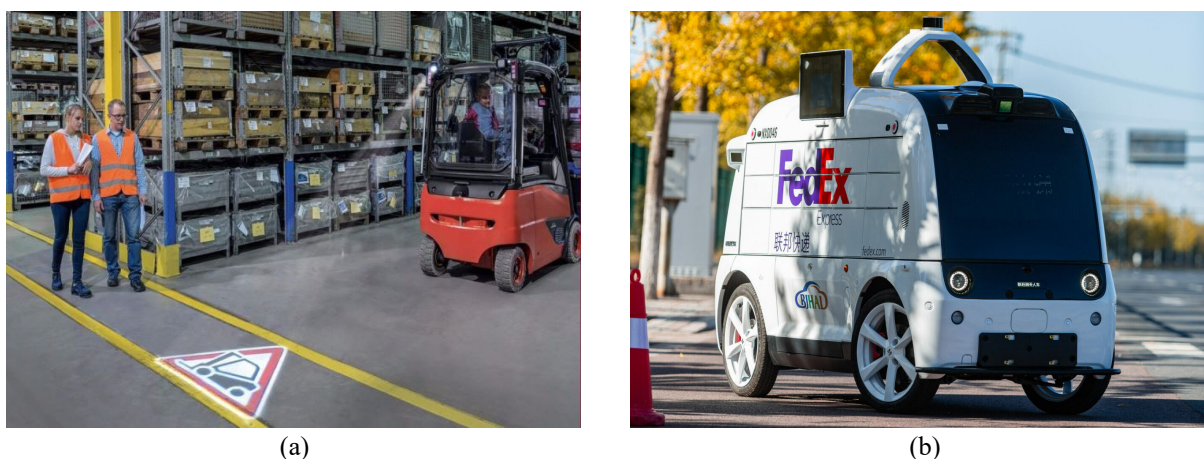


Fig. 5.6 Operation scenario of autonomous forklift (a) and unmanned delivery by the AV (b)

the depart notification with recipients. As regards the extended signals which express these messages, the design liberty is widely open.

In the above, we present several use cases of extended signals involved in the typical AV applications. For them, the communications of safety and comfort-related messages through extended automotive signals can be supposed to benefit the interactions among AVs and their surroundings. In the next steps, further research works can be carried out with regard to them. Especially for the scenarios where extended signals are easier to be valorized, the study on them would be intensely expected by the stakeholders with open arms. Basically, in the vehicle-pedestrian interaction around the crosswalk which is focusing point in this thesis, the extended signals used to communicate the ADS status, the AV awareness of the pedestrian, and the yielding intention are more meaningful for the public safety and the projection of vulnerable pedestrians than for the AV owner. Whether the AV owner would like to pay for the extended signals seems to be questionable. It is mostly the transportation administration that will push their usage on AVs for public road safety. Nonetheless, in the cases where extended signals are helpful for improving customers' safety and comfort, for example the customer picking-up/dropping-off of rental robot cars and buses, and the unmanned delivery by AVs, the involved AV service suppliers can directly profit from the usage of extended signals in terms of the increasing customers. This would encourage the AV service suppliers to employ the extended signals in their AVs. Therefore, the study on these types of use cases would be of great interest for academics and industries. For the use cases of extended signals that we proposed to study, we have suggested in the above some research points in the aspects of signal designs and users' behaviors. It is expected they can help other researchers to study extended signals for AV communication functions on the right track.

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