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Review

Negotiation and Decision-Making for a Pedestrian Roadway Crossing: A Literature Review

Roja Ezzati Amini [1,*], Christos Katrakazas [2] and Constantinos Antoniou [1]

[1] Chair of Transportation Systems Engineering, Department of Civil, Geo and Environmental Engineering, Technical University of Munich, 85748 Munich, Germany; c.antoniou@tum.de

[2] Department of Transportation Planning and Engineering, National Technical University of Athens, 15773 Athens, Greece; ckatrakazas@mail.ntua.gr

* Correspondence: roja.ezzati@tum.de

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Abstract: The interaction among pedestrians and human drivers is a complicated process, in which road users have to communicate their intentions, as well as understand and anticipate the actions of users in their vicinity. However, road users still ought to have a proper interpretation of each others' behaviors, when approaching and crossing the road. Pedestrians, as one of the interactive agents, demonstrate different behaviors at road crossings, which do not follow a consistent pattern and may vary from one situation to another. The presented inconsistency and unpredictability of pedestrian road crossing behaviors may thus become a challenge for the design of emerging technologies in the near future, such as automated driving system (ADS). As a result, the current paper aims at understanding the effectual communication techniques, as well as the factors influencing pedestrian negotiation and decision-making process. After reviewing the state-of-the-art and identifying research gaps with regards to vehicle–pedestrian crossing encounters, a holistic approach for road crossing interaction modeling is presented and discussed. It is envisioned that the presented holistic approach will result in enhanced safety, sustainability, and effectiveness of pedestrian road crossings.

Keywords: pedestrian behavior; vehicle–pedestrian interactions; road crossing; decision-making process

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1. Introduction

Participating in traffic requires road users to continuously interact with one another [1]. During the time spent for transport, traffic participants have to face a great amount of information and react efficiently to it [1–3]. In such a system, it is essential for road participants to manage their own moves, while taking into account the presence of other users, as all of the participants usually share a pre-defined space [1]. These mobile encounters entail a continual monitoring and communicating of users' positions with regards to one another, along with suitable reactions to the features associated with the surroundings [4]. Furthermore, traffic safety in urban settings heavily depends on successful interactions among traffic participants [5]. For this reason, fundamental traffic rules have been established to manage traffic, especially in vehicle–pedestrian encounters. The traffic management and control systems can diminish the conflicts and uncertainty by specifying the right of way for different road users (e.g., traffic rules imposed by different phases of traffic signals at signalized intersections). Road traffic, however, involves many circumstances for which it may not be possible to specify explicit rules [6], such as a sudden change of direction by pedestrian, while crossing the road. Hence, traffic participants and particularly pedestrians extensively rely on communication methods, elaborated over the course of time amongst them, to avoid conflict and solve ambiguous traffic situations [7]. For instance, hand gestures by drivers to convey the message "it is safe to cross" to pedestrians, while there is no traffic control systems on the road segment. The role of these communication cues is dominant in situations in which the right of way is not clearly defined [8], or road users expose unexpected traffic behaviors [9]. In these circumstances, road users employ explicit and implicit signals to communicate their intention regarding either gaining or giving the priority in the crossing scenarios. However, sometimes pedestrians are engaged in multi-tasking (such as mobile-phone conversation, texting, listening to music, reading), and are therefore not able to communicate their movements/intentions with the interacting party. Such behaviors have not been captured in this paper, as the focus is on traffic interactions as a bilateral process among involved road users. In addition to communicating intended movements, traffic interactions require road users to properly interpret and predict the actions of their interactive party. However, this may become problematic in some situations since traffic participants demonstrate different behaviors on approaching the crossing sites. Previous studies have investigated a broad range of factors that may affect the behaviors of road users, namely drivers and pedestrians, on approaching the crossing sites, such as pedestrian walking speed and characteristics, speed of approaching vehicle, road characteristics, etc. [10–14].

Moreover, mobility technologies have been constantly changing in the recent years, as more and more vehicles will have automation functions in the imminent future [15]. The changes of transportation means have inevitably led to an adjustment of road designs, and a new set of rules and social norms emerging to manage the mobility of traffic participants [16]. Since fully automated vehicles will be integrated into the existing transportation system, the interaction with pedestrians becomes challenging in cooperative situations (e.g., when road users require sharing their intentions to communicate the right of way, or to coordinate their reactions) [5,17–21]. This is primarily related to the absence of a human driver in vehicles and thereby an absence of driver cues in vehicle–pedestrian communications, which may decline the trust and confidence of pedestrians [22–25]. To overcome these limitations, the intentions of such vehicles need to be clearly transmitted to other traffic participants [24]. In addition, ADS must have a proper understanding of pedestrians' behaviors and their decision-making strategies to execute appropriate driving maneuvers [8]. The complexity of crossing strategies performed by pedestrians, and difficulty to thoroughly analyze their decision-making process, have also engendered challenges in designing ADS [5,8], insomuch that human road users may act differently from the system's presumptions [16].

The main focus of this paper, therefore, is to review the previous findings of crossing behavior studies in order to investigate how pedestrians negotiate the road crossing with motorized vehicles and make decisions at crossing sites, in which the right of way is not determined by formal traffic rules or road designs. A proper understanding of these matters can provide useful recommendations for designing the ADS, and ensuring a safe, smooth, and efficacious interaction process amongst pedestrians and vehicles [5]. The paper is intended to provide in-depth insights into the following issues:

1. The efficiency of different communication techniques and their impact on behavior of road users have been investigated thoroughly in this paper by reviewing previous studies. How road users react to various communication signals, how a signal is interpreted by receiver, which methods road users choose to communicate their intentions, and how they send the signal are substantial components of traffic communications. An in-depth examination of these elements can assist ADS in forming efficient communication methods with pedestrians.
2. Factors influencing crossing behaviors of pedestrians have been reviewed in order to understand why pedestrians behave differently from one situation to another while crossing the roadway. Since understanding of pedestrians' behaviors is not intuitive [7], a comprehensive analysis of decision-making procedure and factors influencing them is required for the design of ADS [17].
3. The vehicle–pedestrian interaction process includes movements/intentions communications, as well as decision-making processes of interactive parties which are reflected in their crossing behaviors. A vast number of studies have been performed to assess different aspects of vehicle–pedestrian interactions; however, the focus on the entire process has been mostly disregarded due to the complexity of the subject. This is crucial as ADS requires an appropriate

interaction concept for driving safely in urban environments [5]. Therefore, formulating the whole interaction process in the existing traffic context, by considering the role of different communication methods and users' crossing strategies, is vital for designing efficient ADS and external human–machine interfaces (eHMIs).

The paper is structured as follows: Section 2 includes the fundamental definitions, while Section 3 provides an overview of the potential conflict points of pedestrians with vehicular traffic. The interactive parties in various crossing scenarios, presently only human road users, interact with one another by a variety of verbal and nonverbal communication means. These traffic communication methods used by road users on approaching the crossing sites are reviewed in Section 4. The employment of different cues and their impact on the yielding behaviors were also investigated in this section. In what follows, previous studies of crossing behaviors at unmarked/unsignalized crossing sites are reviewed. For this purpose, the behavior of drivers and pedestrians on approaching different uncontrolled pedestrian crossing facilities has been explored in Section 5, to identify factors influencing their crossing-decision strategies.

2. Definitions

Traffic Conflict is defined as an event between traffic participants, in which an evasive maneuver needs to be taken by one of them to avoid a collision [26].

Jaywalking is a term used to describe the action of crossing a road with no regard to the pedestrians' traffic regulations [27].

Traffic Interaction is defined as situations in which the traffic participants adapt their behaviors according to one another [28], as well as interpreting the environmental context, surrounding traffic, and responses to one's own behavior [29,30].

Pedestrian Gap Acceptance (GA) refers to the time or space gap between vehicle and pedestrians [31], and can be determined based on the speed of oncoming vehicles, as well as its distance from the pedestrian crossing [11].

Post-Encroachment-Time (PET) value can be used to describe the time gap, from the moment that one of the interacting road users leaves the potential collision point to the moment another user arrives at it [32].

Time-To-Collision (TTC) value is the time between approaching road users and the potential collision point [33], and can be used to describe the severity of conflict events [32].

Time-To-Arrival (TTA) estimation can be used to evaluate the time gap perception between approaching vehicles and the own position/a person/specific place [10,34].

Time Advantage (TAdv) as an indicator describes the expected PET value for each moment, considering an unchanged speed and paths of road users [35].

3. Vehicle-Pedestrian Safety Considerations

Most vehicle–pedestrian collisions occur when pedestrians cross the roadway illegally at locations out of crosswalks, or at pedestrian crossing facilities particularly with lower protection [36–39]. Traffic participants may not comply with formal traffic laws for reasons, such as lack of sufficient knowledge about the rules in specific situations or the ambiguity of rules, which may be understood differently by users [40,41]. Some of the traffic rules may also not perfectly correspond to the road design or the natural human behavior patterns [40]. Dey and Terken [42] claimed that the lack of strict enforcement like traffic lights at uncontrolled pedestrian crossings may result in disregarding users' right of way by drivers. In a similar manner, in the absence of crossing facilities in a road segment, pedestrians may adapt mid-block crossing and jaywalking, in order to avoid detour and shorten the travel time (instead of walking an additional distance to a crosswalk) [42–45]. Such unpredictable crossing behaviors by pedestrians create a potential critical conflict with approaching vehicles, as well as interrupting the normal traffic flow [46]. However, the majority of road users interact without any serious conflict and are therefore of little/no interest from a traffic safety point of view [16]. The interactions may be important from the user experience perspective, which may result in unpleasant interaction experience, and therefore encouraging/discouraging specific behaviors or road designs [16]. In addition, pedestrians are notified of the spots to cross the road by marked crosswalks and signs, but there is still no standard agreement for them to indicate their crossing decision intention in advance of drivers, besides standing in/at the crosswalk [47]. However, pedestrians stepping into the roadway, or signs and markings may induce drivers to give way to pedestrians at crossings, but there is still no effectual and certain prompt that a pedestrian, who has commenced crossing, can use to enhance the possibility of a driver yielding [47–49], since there are still some situations in which drivers do not give way to pedestrians who stepped into the street. For instance, an observation study on zebra crossings showed that about 30% of pedestrians continued walking when the vehicle was approaching, and the vehicle took the evasive action to avoid collision [13], whereas, in 4% of the situations, the pedestrians either retreated or ran from the path of the vehicle to avoid collision [13]. Occurrence of the aforementioned scenarios signifies the necessity for utilizing some additional techniques by road users to communicate their movement intentions in advance of the interacting party. Therefore, a variety of communication methods, which are mostly based on the human communication principles, have been developed between human road users in order to avoid conflict and resolve ambiguity regarding the right of way.

4. Communication between Traffic Participants

Communication is an essential element of traffic interactions, as it assists human users with resolving ambiguous circumstances on the road [50]. Traffic participants communicate a range of actions regarding their intended movement, such as going straight, stopping, and going ahead of someone [51]. For an efficient communication, the interacting parties need to understand the intentions of one another, as well as the situation in which the communication is occurring [52]. Since it varies from one situation to another and it always depends on the circumstances [21], this also requires communicators to anticipate each other's future actions [7,21,52]. However, anticipations and expectations concerning the other's behavior may not always be correct [53]. The situation may also become problematic when traffic participants behave according to contradictory formal and informal traffic rules, in which the traffic participant's ability to rightly anticipate another user's behavior declines [53,54]. Traffic interactions are also relatively short, which limits the opportunities to communicate among traffic participants [37]. This may oftentimes lead to misunderstanding and misinterpretations and thus annoyance amongst participants [37]. Furthermore, the need for social interaction among drivers, cyclists, and pedestrians is more substantial in urban traffic [50], and mostly occurs in the front and the side of the car [25]. The actions employed by interactive parties to convey their movement intentions can be classified as different communication methods, as discussed in the following subsections.

4.1. Anticipatory Behaviors of Traffic Participants

Anticipatory behaviors are minor activities performed by road users that make others able to predict their intentions [6]. Examples of such behaviors include changes in walking speed or placing a foot on the road, which in general helps drivers to anticipate a potential crossing intention for a pedestrian [6,10]. These behaviors are classified as one of the informal and non-regulated communication methods among road users to anticipate what action another user may possibly do [10]. Another anticipation of traffic participant's behavior is associated with the physical characteristics of communicators. This communication signal is the same as what is named "schema formation" by Merten [55] in grouping different communication choices. For instance, the physical traits of pedestrians can give drivers clues about their age and their mobility behaviors, while elderly pedestrians may walk slower than younger ones [6], or children may have more unpredictable behaviors than adults. Pedestrians can also utilize the same available information on the road about the vehicle's model/category, e.g., the driver of an ambulance may behave differently from a van driver [6].

4.2. Human Driver Communication Methods in Interaction with Pedestrians

Drivers anticipate the intentions of other road users by interpreting various nonverbal communication cues. This is mostly presented among drivers and pedestrians, while negotiating right of way [20]. Although the decisions of drivers are affected by the traffic regulations on the road, there is still some uncertainty in circumstances, where the traffic laws are not sufficient [56]. These situations can occur at uncontrolled intersections, transition of traffic signals, merging/changing lane, multi-lane roundabouts, etc. [56]. From the vehicle's point of view, communication style can be classified as implicit and explicit [12,21]. These terms are defined below:

- ***Implicit Communication*** (also referred as informal communication): In general, when the content of a message is indirectly included in that instead of clearly being stated, then the message is conveyed implicitly [21]. In terms of traffic, implicit communication refers to using non-regulated communication cues to negotiate the driver's intention, or to help communicators to anticipate future actions of them, e.g., deceleration to encourage the pedestrian to cross [10,21,57].
- ***Explicit Communication*** (also referred as formal communication): A message is transmitted explicitly, if the sender transfers intention directly to the receiver by using clear cues [21]. In traffic situations, explicit communication usually refers to using light and sound signals to communicate the intention of vehicles [21]. Explicit communication includes defined/regulated communication means. Horn, turn indicator, emergency lights, warning lights, brake lights, and even labelling a car (as an ambulance, automated vehicle, police, etc.) are examples of this type of communication [6,21,53]. Nonverbal behaviors are usually used to transfer implicit messages; however, in traffic, nonverbal communication methods are used for sending explicit messages [58,59]. Hand gestures executed by drivers to signal pedestrians that they can cross in front of the car safely, or expression of gratitude to a fellow driver by waving a hand are examples of explicit cues performed by drivers in traffic encounter [6].

4.3. Pedestrians Communication Methods in Interaction with Drivers

Pedestrians mainly interact with other road users by using nonverbal communication signals. However, in some situations, the message transferred via nonverbal cues is missed, ignored, or not correctly comprehended by the interacting party [60]. The main nonverbal communication signals used by pedestrians are:

- ***Gaze Direction***: The most significant message that is essential to be transferred to pedestrians is whether they have been seen [6]. Therefore, in the crossing scenes, they mostly establish eye contact with drivers or wait to receive an explicit cue from them to confirm that they have been detected, and the driver will yield if they start crossing [6,61,62]. If the driver who receives the signal returns the eye contact, then pedestrians presume that they have been seen [63]. Moreover, head orientation, which occurs with the purpose of looking or glancing at the approaching traffic, can be a robust sign of crossing intentions by pedestrians [64]. However, traffic participants behave differently in the various traffic settings [64]. For example, pedestrians intending to cross a road are more likely to cross without looking at the oncoming traffic in the presence of traffic signals and stop signs, since they expect drivers to obey the traffic rules [64], whereas, in the absence of traffic regulations, they frequently monitor the approaching traffic and mostly establish eye contact with the driver to assess the environment and whether the driver may give way [64,65].
- ***Hand Gesturing***: Gestures are described as efficient nonverbal signals amongst road users, which are mostly interpretable and explicit [6,66]. However, the concept of the message transferred by using this kind of signals can vary from situation to situation. For example, hand gesturing

can show thankfulness, giving priority, or requesting the right of way, while the responses are in the form of changes in pedestrian behavior like deceleration, acceleration, or stop [64,67,68]. According to previous studies of driver's interaction with the environment, three fundamental dimensions have been defined to evaluate a signal: visibility, clarity, and motive power [66,69]. From the visibility point of view, gesturing a dynamic signal is found to stand out more than traffic signs and road markings, since driver's attention is more easily caught by moving rather than static objects [70]. Clarity, on the other hand, varies across gestures, as some are more effective than others. Finally, driver compliance may vary according to the concept of the gestures, i.e., whether they are commanding or polite [66]. This can reflect compliance obtaining strategies through "assertion" and "direct request" [66,71].

4.4. The Impact of Communication between Road Users on Traffic Behaviors

Road users communicate with each other through various unregulated methods, which include their movements and positioning, as well as establishing eye contact. According to previous studies, these interactions have a vital role in forming a smooth and efficient traffic flow, as well as improving safety [7,21,25,50,72,73]. Road traffic is fundamentally directed by a range of official regulations, which define the right of way for traffic participants in various road designs and facilitate social interaction [37]. Furthermore, in many countries, drivers give way to pedestrians to protect them at pedestrian crossings or unregulated crosswalks [66]. However, drivers may be more likely to conform with the official traffic control regulations rather than gesturing or gazing cues displayed by pedestrians [74]. Road users, particularly drivers, may also receive informal communication signals from authorized traffic directors, which is mostly by means of hand gesturing [75]. On the other hand, pedestrians may employ nonverbal communication indicators only when an expected driving behavior of an oncoming vehicle has been contravened [42]. In these situations, pedestrians are looking for a confirmation of intent from the drivers before carrying out their crossing decisions [42], while most drivers give way to pedestrians who have already stepped into the street, but there are still some drivers who ignore the pedestrian's right of way, and speed up or swerve to pass them at crossings sites [76]. For example, an observation on Columbus, Ohio showed that the majority of drivers never came to a complete stop, and 43% of them did not stop with pedestrians walking in the crosswalk [76]. Another study revealed that more than a third of drivers (36%) failed to yield to pedestrians at uncontrolled marked crossings [53].

In the process of negotiating priority in driver–pedestrian interactions, either pedestrian or driver has to give way. Pedestrians give way to drivers by making the roadway clear for them to cross by, for example, waiting at the curb or stepping out of the road. On the other hand, a driver yields by; (1) a reasonable complete stop (hard yield), (2) delaying vehicle arrival at the crosswalk enough to create a crossing opportunity for the pedestrian (rolling/soft yield), and (3) slowing down and eventually stopping for an extended duration before restarting movement (hard yield and stop) [46,48]. In hard-yield conditions, the driver is usually too close to the crosswalk during a crossing activity and must stop momentarily, while soft-yield is a condition based on the driver's observations and anticipations of pedestrian action [46]. On the other hand, pedestrians cross the roadway first in three circumstances: (1) before the arrival of the vehicle and without influencing its speed, (2) when the oncoming car is motivated to stop by a pedestrian who does not stop before crossing, and (3) when the approaching vehicle brakes on the driver's own initiative to yield to pedestrian (ideal situations) [32]. Such [37] classified eye contact as a means of communication for both drivers and pedestrians at crosswalks considered by pedestrians when deciding to wait/go, and by drivers as a way to force pedestrians to stop. A study to assess the influence of pedestrian's gaze on driver's yielding behavior at pedestrian crosswalk showed that gazing increased the number of drivers who gave way to pedestrians [77,78]. In contrast, another research paper indicated that nonverbal communication signals, such as eye contact and gestures, do not play a significant role in crossing negotiation [42]. Another experimental study criticized the possibility of performing mutual eye contact between pedestrians and drivers [79]. The results showed that over 90% of the participants cannot determine the gaze of the driver at 15 m and see the driver at all at 30 m. The authors then argued that, considering the speed limit of 25 mph in urban settings, more than 99% of pedestrians would have begun crossing, before being able to see either the driver or the driver's gaze. An experimental study performed in Beijing, China evaluated the impact of various pedestrian hand gesturing on driver yielding rate at non-signalized crossings, which showed a slight increase in the overall yielding rate among drivers when pedestrians performed hand gestures [66]. The same study in the US also showed greater yielding rates at uncontrolled marked crossings when pedestrians displayed hand gestures, compared with not using hand movements [47]. Most of these informal traffic rules and communication methods are developed through traffic participants' interactions, and based on expectations about other participants' behavior, mostly when formal traffic rules do not correspond with the road design [40]. The expectation about the behaviors of other interacting agents can be formed due to the chosen strategies or transferred communication signals. However, the interaction strategies executed by road users may be influenced by various factors, such as interaction environment or road users' characteristics, and need to be correctly interpreted.

5. Crossing Behaviors of Traffic Participants

Traffic participants manifest varied behaviors on approaching a crossing site. Drivers, as a party in the interaction with pedestrians, have several strategies to decide whether or not to give way to pedestrians. These strategies are subject to several factors, such as speed of the vehicle on approach, or its distance to the common spatial zone with pedestrians. Zaidel [80] discussed that every driver is influenced by social environment factors, including other traffic participants, general social norms, and formal traffic rules. Every traffic participant is also a part of other participants' social environments [80]. Social environment can influence drivers in four different ways: (1) communication with other participants, (2) behaviors of other participants as a source of information, (3) other participants as a reference group, and (4) emulation of others. Another common strategy utilized by drivers to coordinate their behavior is "movement pattern", showing how road users communicate their intentions through their movements [81]. For example, on approaching crosswalks, drivers stop before where they legally must, signaling their intent to wait for others to take the right of way. Then, they move forward slowly to indicate that they will take the right of way next [81]. In addition, the meaning of road users' actions can only be comprehended in the context of their occurrence [81,82]. Therefore, the meaning of the actions of a single road user cannot be understood by looking at the actions alone, and must be interpreted by considering the whole road system, containing road users, road geometry, etc. [81,82].

On the other hand, it is important to understand under which circumstances pedestrians feel safe to cross, and which factors influence their crossing-decision strategies. Pedestrian crossing behaviors are oftentimes accompanied by some sort of signals and information to indicate their crossing intentions to the approaching vehicle, such as forward movement, stepping into the road, leaning forward, putting one foot on the road, looking at oncoming vehicle, informal signals, etc. [81]. Distance between agents, as a result of movement, also influences pedestrians' expectations regarding the other traffic participants' behavior [83]. In addition, pedestrians cross the roadway in different ways, based on the speed of oncoming vehicles, available gaps, and number of lanes: (1) single stage, (2) two stage, (3) and rolling [43]. Pedestrian crossing behavior can also be classified into three phases: (1) approaching (without changing the walking speed), (2) appraising (decelerating due to the speed and distance of approaching vehicles), (3) and crossing (acceleration) [84]. It is also possible for a pedestrian to step backwards or run to avoid collision with vehicles, when the gap is not long enough to complete the crossing [36]. However, the majority of pedestrians waits before crossing, until the vehicles come to a complete stop, instead of relying on their own perception of whether it is safe to cross [53]. The factors, identified in the literature, influencing the crossing behaviors of users are presented next:

5.1. Pedestrian-Associated Factors Influencing Crossing Behaviors

5.1.1. Pedestrian Characteristics

Age is one of the factors influencing pedestrian behavior, meaning that people of different age groups may have various crossing behaviors. Road crossing is a challenging cognitive task, which makes safe traffic judgements difficult for children younger than 9 years old. It may even take until the age of 11 or 12 for children to fully develop all required abilities and gain an adequate understanding of the concept of traffic rules [85,86]. In addition, the lack of experience among young children in crossing roads can make them incapable of making safe decisions, and therefore is a concern for roadway designers. This is along with unpredictable behaviors, inattentiveness, and problematic risk perception, which have been found to be the leading reasons for child pedestrian accidents [85–87]. On the other hand, older pedestrians demonstrate more conservative behaviors in comparison with younger people [10]. For example, the percentage of pedestrians 65 years and older crossing on red phase is notably lower than the percentage of younger pedestrians [88]. However, physical conditions of elderly pedestrians restrict their abilities to precisely judge the traffic situation and speed of approaching vehicles, and lead to difficulty negotiating curbs, and excessive start–up time before leaving the curb [86,89]. Bennett et al. [90] observed different average of start time loss of 2.68 s and 1.3 s for all groups of pedestrians at signalized intersections and controlled mid–block crossing sites, respectively. The start–up time to initiate the crossing is also higher among distracted pedestrians than non-distracted pedestrians [91]. On the other hand, middle-aged adults are found to be more aware of the traffic environment by looking at oncoming traffic more frequently before crossing the road, having a larger safety margin, and better perspective skills [36]. Alcohol impaired pedestrians (in the 1980s, around 44% of killed/injured pedestrians had BACs (Blood Alcohol Concentration) of 10% or greater) and pedestrians with physical disabilities also have different behaviors due to the mobility impairment [92].

Pedestrians' behaviors can be also different because of their gender. For example, females seem to wait longer during the red phase of signalized crossings before attempting illegal crossing than males [93]. Female pedestrians may also demonstrate less risk-taking behaviors at crossings, compared with males [13,94]. In contrast, another observation of pedestrian behavior at crosswalks exposed no difference between female and male risk-taking behaviors while crossing [95].

5.1.2. Pedestrian Walking Speed

One of the most fundamental elements of human movement behavior in urban spaces is walking speed, as it is a dominant parameter of most microscopic simulation models, and which can be affected by individual pedestrian behavior and habit [14,96]. Walking rates vary among different studies [14,86,92,97]. In accordance with Manual on Uniform Traffic Control Devices (MUTCD), the average walking speed for typical groups of pedestrians is 1.22 m/s, suggested as a basis to evaluate the sufficiency of the pedestrian clearance interval at traffic signals with the possibility to extend the phase for slower pedestrians by pressing a push-button [92,96,98]. The recommendation for the design of traffic signal timing without an actuator is lower—0.91 to 0.99 m/s [99]. However, pedestrian crossing speed may also vary for different countries, for instance a study showed 1.53 m/s for the average of crossing speed at intersections and mid-block crossings in Melbourne, Australia [90], the average of 1.34 m/s in Jordan [100], 1.39 m/s at non-signalized crosswalk in Malaysia [101], and 1.4 m/s as the design speed by the Turkish Standards Institution [102].

Walking speed declines by increasing age, as a study showed an average walking speed 1.53 m/s for pedestrians younger than 16 years old, while 1.16 m/s for those older than 64 years old [14,103]. In addition, the elderly, pedestrians with disabilities, and those pushing baby prams or walking along with younger children tend to walk at slower speeds [14]. Different walking speed can be also related to the gender, as some studies showed that, on average, males walk faster than females [96,104]. The group size can be another factor influencing the walking speed, since people in a group of two or more walk slower than individuals and take longer to complete the crossing process [14,46,104,105]. It is also found that environmental factors, such as weather, time of day (slightly higher during the morning and evening peak period), type of facility, and the overall function of pedestrian area (e.g., shopping, school, business) also affect the walking speed of pedestrians [14,106]. For example, pedestrians walk faster at signalized intersections than the mid-block locations [90], when crossing roadways than walking in a footpath [14,107], or when the traffic volume is high [104,108]. This might even turn to running in some circumstances: at signalized crosswalks to use the limited green-light phase left to traverse the roadway, or at uncontrolled unmarked crossings or illegal sites to traverse the road from the start of the lane to its end before arrival of approaching vehicles [36,109]. The latter one may cause a new independent crossing task for pedestrians at each lane requiring a new evaluation of the traffic situation and possibly adjustment of the crossing manner, which may again change their walking speed.

5.1.3. Pedestrian Group Size

The size of pedestrian platoons is associated with both pedestrian crossing behavior and driver yielding behaviors. As the number of pedestrians waiting at crosswalks increases, the likelihood of drivers' yield increases. The probability of yielding is two times greater, when the number of pedestrians waiting increases from three to six persons, since a big group captures more attention of drivers for yielding than smaller groups [11,53,110]. It has also been found that the possibility of a group of four pedestrians continuing to traverse crosswalk is 70% higher than individual pedestrian [13]. This also enhances safety of pedestrians, as pedestrians in groups are more detectable [36]. Due to the frequency of crossing, smaller pedestrians' platoons cause more traffic interruptions and higher cumulative delay, and consequently driver inconvenience compared to bigger platoons, which cross at once [46]. Analyzing the impact of pedestrian platoons on yielding rate at illegal mid-block crossings also revealed that the rate of "hard-yield and stop" increases significantly by increasing the size of groups. This shows that pedestrians in groups require longer crossing time, which might not be provided by rolling/soft yield. Hence, drivers have to stop approaching the crossing points, which may trigger a traffic wave and last until pedestrians cross. As a result, drivers may slow down proactively on approaching a crossing point in anticipation of a pedestrian crossing maneuvers, particularly if there is a pedestrian platoon waiting by the roadside [46,111]. Moreover, it is observed that the waiting time of pedestrians at zebra crossings reduces by increasing the number of pedestrians at crosswalks [94].

5.1.4. Pedestrian Presence at the Curb

The only possible way for pedestrians to indicate their crossing intention is to stand at the curb side [47]. However, studies showed that the presence of pedestrians at the curb side does not necessarily lead to changes of driver behavior in terms of sufficiently adapting the speed on approaching the zebra crossings [32]. Pedestrians waiting at curb sides, without any attempt to cross, may even increase driver tendency to not give way to pedestrians [37]. An observation at a zebra crossing showed that almost none of the drivers yield to pedestrians who were waiting at the curb and looking at the oncoming traffic/drivers [112]. However, pedestrian distance to the curb is found to be one of the most significant explanatory variables influencing the behavior of drivers, and is utilized to model the probability of a driver braking [13,48]. A study on users' behaviors at crosswalks showed that drivers are less likely to yield if a pedestrian was waiting more than half a meter away from the curb [53]. Furthermore, when the pedestrian is already on the crossing, the probability of driver reaction increases as the pedestrian's distance from the curb/refuge increases [13]. At uncontrolled mid-block crossing, higher risk-taking behaviors of pedestrians at central refuge islands is found to be associated with longer waiting time at the first curb (30 s waiting time or more [113]) as pedestrians become impatient to cross the roadway [94].

5.2. Environmental and Dynamic Factors Influencing Crossing Behaviors

5.2.1. Gap Acceptance

From pedestrian perspective, time, or distance gap with the closest oncoming vehicle must be long enough for safely crossing the road [48,114]. The required time for pedestrians to cross can be described as "critical safe gap", and it is computed based on the crossing length and pedestrian crossing speed [115]. Sun et al. [11] stated that there is a remarkable difference between the pedestrian GA behavior and driver GA, due to the higher speed of motorized vehicles compared to the pedestrian's speed. Pedestrians need larger gaps for a safe crossing maneuvers, which may result in longer waiting time and thus increased risk-taking behavior to accept shorter gaps [11]. The likelihood of pedestrians accepting shorter gaps also declines, when they are in a group than individual pedestrians. Moreover, the minimum gap accepted by younger pedestrians is smaller than the minimum gap accepted by elderly pedestrians [10,11]. It is also observed that pedestrians accept a shorter gap, while waiting on central refuge islands, compared to the curb side [94], or in narrow streets rather than wide environments [63,115]. A study in the UK showed that all pedestrians accepted 10.5 s gaps between approaching vehicle, while no one accepted gaps less than 1.5 s [116]. Accordingly, "pedestrian critical gap" reflects the minimum time interval, in which no pedestrian commences crossing [96]. Estimation of critical gap is based on the greatest and smallest accepted gap for a given intersection [96], and can vary among road users depending on road geometry, vehicle features, and pedestrian characteristics [10,11,48,63]. For instance, heavy vehicles accept larger gaps and have greater courtesy towards pedestrians to compare with passenger cars [11,96]. Pedestrians also accept available shorter and riskier gaps, when they wait too long for the critical gap [117]. A study at unsignalized crossings found that pedestrians sought rolling gaps in high traffic volume, meaning that pedestrians do not wait for all lanes to be clear; instead, they predict where a gap will be available in the next lane [118].

5.2.2. Speed of Approaching Vehicle

The speed of a vehicle approaching a pedestrian crossing is one of the most important factors that pedestrians consider, when making the crossing decision [12,37]. However, pedestrians may have some difficulties in estimating the speed of approaching vehicles [13]. Vehicle speed is also identified as a factor influencing yielding behavior [114,119], where lower speeds are associated with increased yielding behavior [13,53,120]. A study in Helsinki, Finland, found that the reacting probability of drivers traveling at the speed of 50 km/h is nearly zero, when individual pedestrians are just waiting at the curb, without stepping on the street [13]. Driver's acceleration strategy (or no deceleration) on approaching pedestrian crossings is interpreted as an implicit signal to show their tendency to maintain priority, and not giving way to the pedestrians (see Section 4.2) [37]. However, speed adaptation prior to reaching pedestrian crossings is a significant factor to ensure pedestrian safety [121]. For this reason, a sufficient distance between oncoming vehicle and crosswalk is required for drivers to react submissively to an unexpected emerging pedestrian [32]. Drivers may also be forced to slow down (anticipatory avoidance response) or stop (delayed avoidance response) in some risky circumstances [32]. For example, when pedestrians who commence crossing: do not look at the oncoming traffic, are distracted and running/stepping into the roadway, show sudden/unexpected pedestrian's movement, or are jaywalkers [37,110].

5.2.3. Road Characteristics

Road environmental factors, such as road width to be crossed by the pedestrian, total road width, number of lanes, and various pedestrian engineering and crossing treatments, may influence the pedestrian–driver interactions in terms of the perceived safety of crossing and the road users' anticipation of different types of behaviors [12,48,122]. For example, a study by Turner et al. [119] showed that the number of lanes crossed was a significant predictor of motorized vehicles yielding rates. The drivers' yielding rate may also vary among different types of pedestrian crossing facilities with various levels of control. Previous studies showed noteworthy difference in the number of drivers who adhere to the traffic rules by yielding to pedestrians at different crossings: 4–45% at marked unsignalized crossings [123–126] vs. 17–94% at marking crossings with one type of traffic management and treatment, or written social assistance [48,76,119]. The yielding rate also varies at marked uncontrolled crossings at entry (higher) and exit (lower) legs of roundabouts [48]. On the other hand, pedestrians may feel safer, when the width of the crossing is shorter [53,127,128]. Pedestrian refuge islands and high visibility markings can also produce better compliance rates on roads with lower speed limit [119]. However, Himanen and Kulmala [13] found that road width and the existence of refuge had no significant effects in modeling the driver and pedestrian behaviors at pedestrian crossings.

5.2.4. Size of Approaching Vehicle

The size of vehicles can influence the behavior of both pedestrian and driver, and is an important factor for modeling of road users' behaviors [11]. For instance, the possibility of pedestrians continuing to walk is lower by 20%, when the oncoming vehicle is a lorry or bus instead of a passenger car. The number of attempts by pedestrians to cross also declines if the oncoming vehicle is a heavy vehicle, like a bus or a coach [94]. The probability of drivers reacting is also 30% lower amongst heavy vehicle drivers than car drivers [13].

5.2.5. Traffic Volume

Traffic density is a factor that pedestrians consider, when making the crossing decision; high traffic density is considered as a risky situation [12,37]. Pedestrians also make more attempts to cross the roadway in heavy traffic volume and may be more likely to accept shorter gaps from individual vehicles than platoons [48,94]. On the other hand, the driver's tendency to give priority to pedestrians declines in high traffic volume [13,48,53,129]. Moreover, the possibility of the lead driver reacting decreases by increasing number of approaching vehicles. In a group of five vehicles, the probability of reacting can decrease by almost 40% more than with only one vehicle [13].

5.2.6. Traffic Behaviors and Situations

Traffic behaviors and situations like the presence of a downstream queue after the crossing [48], yielding event in the opposite direction or adjacent travel lane [48], the gap between the car in front and the one following behind it [12,46], distance of the oncoming vehicle [12,46], or driver's direction of approach towards the pedestrian [13], may have some impact on the amount of risk perceived by road users, and thus their crossing-decision strategies.

5.3. Other Contributing Factors

In addition to the aforementioned factors, there are some other elements and circumstances surrounding the interaction, which may influence the decision-making process at crosswalks. Such factors include:

- User familiarity of the place (frequent use of a particular crossing point) can be linked with the higher risk taking behaviors of pedestrians and lower waiting time at crossing [37,94]. It also affects drivers' behaviors on approaching a road segment with no pedestrian facilities. For example, drivers who are familiar with a road segment are likely to drive cautiously in anticipation of pedestrians' unexpected crossing attempt [111], whilst the pedestrian behavior may be surprising for those who are not familiar and can lead to conflict [46].
- Size of the city [13].
- Cultural differences, which can influence the crossing behaviors and the interpretation of informal traffic rules [81,130]. Social norms, cultures, and faith in different countries may influence the

risk perception of users in crossing scenarios, and therefore their crossing behaviors [131,132]. As Western cultures are found to be more risk-prone in road crossing than Asian cultures [132–135]. Pedestrian crossing speed, and gap acceptance are also some of the factors that might be effected by road users' cultures [90,99]. Communication signals employed by road users and their implications may also being interpreted differently in varied cultures [136]. For instance, the meaning of hand gestures, or honking a horn in India may differ with the translation of such behaviors in Germany.
- Visibility, light and weather conditions [10,114,137,138].

5.4. The Correlation of Crossing Behaviors with Surrogate Safety Measures

Surrogate safety measures, as the name implies, are proposed as alternative or complementary methods to identify safety issues [139]. The studies reviewed in this paper have shown some correlations between these indicators and various pedestrian crossing behaviors and factors influencing them:

- The probability of pedestrians crossing the road increases by higher TTC values [63]. A study by Schroeder [48] showed that the TTC threshold is satisfied, if the TTA at the crosswalk is less than 3 s (similar finding as [63]), and everyone crossed the road, when TTC was above 7 s. He, then, analyzed the effect of different treatments at uncontrolled mid-block crossings on yielding behavior. According to this study, TTC declined after treatments' installation. It is also necessary to mention that the expected value of TTC is correlated with the dependent variable yield, in which TTC is lower at non-yielding events compared with yielding ones [48].
- With respect to TTA indicator, an acceptable gap to execute a safe crossing maneuvers may be determined by factors like the level of users' risk acceptance, or pedestrian's perception of how long the gap is [43,137]. However, the perception may not be always correct and might be much longer/shorter than the person's perception [10]. Hence, a pedestrian is required to make a comparison between two microscopic parameters to decide whether it is safe to cross or not [10,12].
- Road users with larger TAdv are most likely to be the first ones who pass the common zone. However, if the TAdv is small, the second user may accelerate with the aim of passing first instead. This is mainly observed when one of the users is "stronger" than the other e.g., private car vs. pedestrian [32,35].

6. Synthesis

Walking is the most widely used mode of transportation and is subject to a considerable risk of injury or fatality on the road, which is mainly caused by motorized vehicles. The majority of these traffic fatalities and injuries occur at pedestrian road crossing scenarios in urban settings at either pedestrian crossings or illegal locations out of crosswalks. However, many road users interact with one another without any serious conflict and are not of interest from a traffic safety perspective, but vital in terms of road users' experience. Traffic interaction, therefore, has been expanded to involve less critical conflicts. Drivers may neglect the pedestrians' right of way at some pedestrian crossing facilities with less strict traffic enforcement, and pedestrians may attempt mid-block crossing or jaywalking in the absence of crossing facilities or just to shorten the travel time. In such situations and more ambiguous circumstances, human road users are required to communicate their movement intentions with another interacting party to resolve the ambiguity regarding the right of way. For an efficacious vehicle–pedestrian interaction process, users ought to indicate their own intentions, understand the other's intentions, and anticipate their next actions.

This cooperative procedure complies with the human interaction fundamentals in which the interacting agents form a mutual behavioral compliance, while responding to each others actions. Furthermore, the situation in which the communication is happening needs to be correctly understood by traffic communicators. Finally, with respect to all prerequisite input information in such traffic scenes, road users utilize a broad range of implicit and explicit communication methods to coordinate their actions with interaction partners. These signals are mostly transferred to acknowledge that interacting parties are seen by another one, confirm their intents, or to influence each other's yield/not-yield decision strategies. A significant number of the reviewed studies in this paper (approximately 29%) found that pedestrians use some form of nonverbal cues such as hand gesture, gaze, or head movement to indicate their crossing intentions to the oncoming vehicles (see Figure 1). In addition, 25% of the reviewed papers revealed that drivers utilize various explicit signals, such as light indicators, horn, or hand gesture, to communicate with pedestrians on approaching crossing sites. In addition, the majority of reviewed studies (39.3%) emphasize the importance of eye contact establishment between drivers and pedestrians, while communicating their movement at conflict points. However, pedestrians may not always receive a response from drivers by returning eye contact, and instead may receive signals, such as hand gesture or light indicators. A smaller number of reviewed studies (7%) indicated that using communication signals among traffic participants has no impact on yielding and traffic behaviors of users.

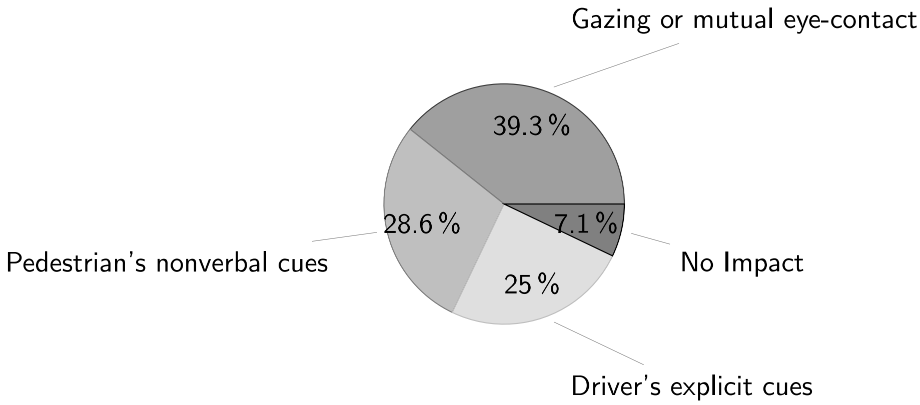
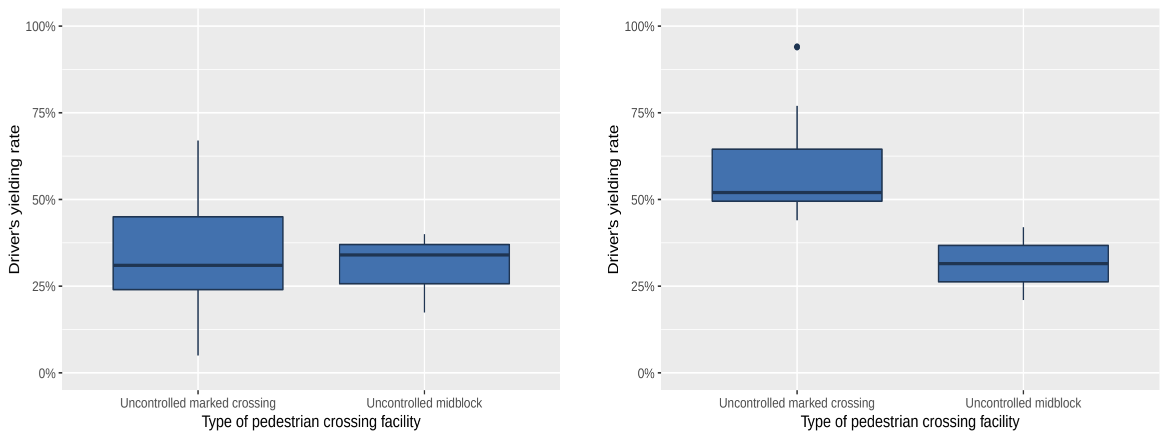


Figure 1. Share of reviewed literature emphasizing the impact of nonverbal cues on traffic behaviors. Source: own elaboration, based on the reviewed references in this research.

On the other hand, the driver's willingness to yield to pedestrians varies among different studies. Figure 2 illustrates the driver's yielding rate at various uncontrolled crossing facilities reviewed in this paper. In Figure 2a, the crossing facilities have no treatment interventions, while Figure 2b shows the rate at crossing sites with at least one treatment implementation, such as warning signs, or pedestrian actuator signals. It is necessary to mention that, in Figure 2b, uncontrolled marked crossing category includes some mid-block crossings' rates, which were considered as uncontrolled marked for the ease of use (e.g., the average of yielding rate for each treatment is representing all type of studied crossings in the study performed by Turner et al. [119]).

In addition, in the priority negotiation process, drivers have some strategies to decide whether or not to give way to pedestrians. A number of factors also influence the crossing-decision strategies of pedestrians at crosswalks to decide whether or not cross the roadway. Figure 3 indicates a summary of all influencing factors in the decision-making process of road users identified in the reviewed literature. The figure illustrates how many times the influencing factors are found to be relevant in the reviewed studies in relation to the total number of reviewed studies. As demonstrated in the figure, the impact of road characteristics, pedestrian age, walking speed, group size, and the speed of oncoming vehicle on behavior of traffic interacting parties have been highlighted in previous studies reviewed in this paper, while the environmental and dynamic factors have presented a higher effect. Some of these factors also influence one another in the crossing scenarios, meaning that the presence or the quantity of one can affect another. Figure 4 illustrates the interrelationship between factors according to the reviewed literature.



(**a**) (**b**)

Figure 2. Driver's yielding rate at uncontrolled crossings in the reviewed literature: (**a**) with no treatment interventions; (**b**) with treatment interventions. Source: own elaboration, based on [13,32,48,53,76,112,119,123–127,140].

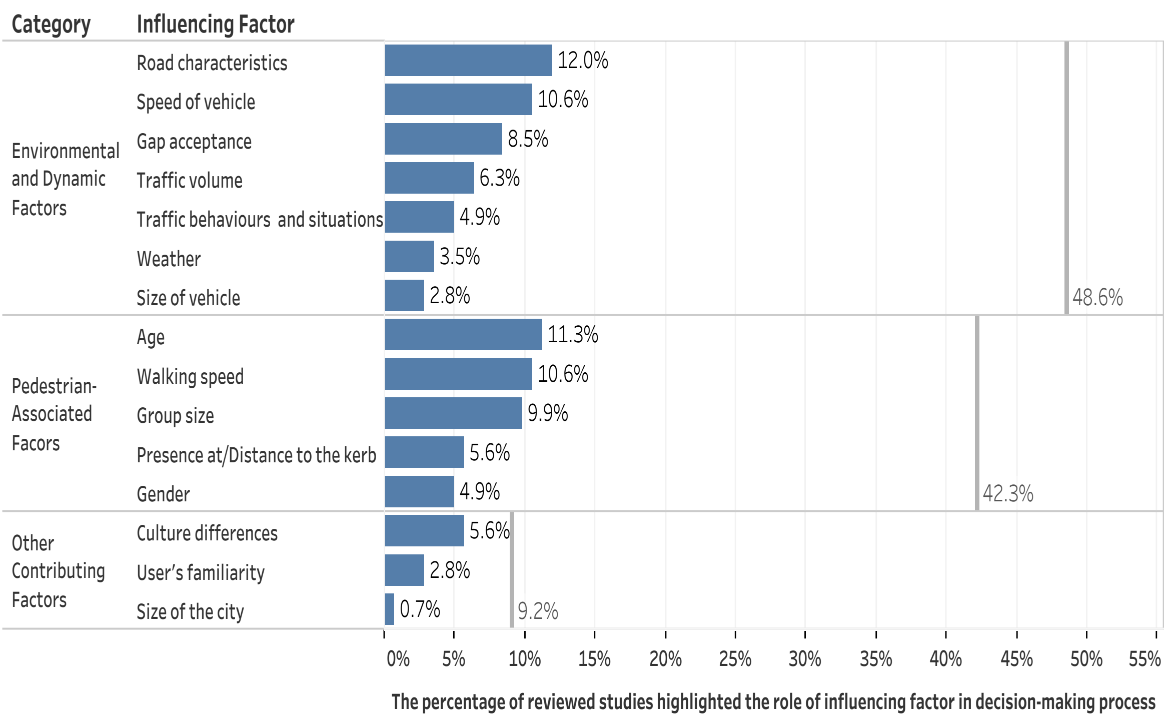


Figure 3. Influencing factors in decision-making process of road users at crosswalks, and the percentage of studies highlighted their impacts with respect to the total number of reviewed studies. Source: own elaboration, based on the reviewed references in this research.

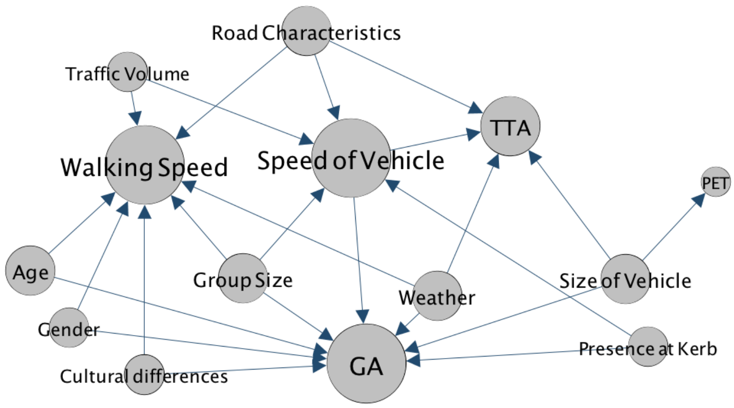


Figure 4. Interrelationship between factors influencing crossing-decision strategies of pedestrians. The direction of arrows shows influence direction from one factor to another. The size of the circles changes based on the number of factors influencing them or being influenced by them. Source: own elaboration, based on the reviewed references in this research.

7. Discussion

The state-of-the-art in negotiation and decision-making for pedestrian road crossings has achieved significant progress on identifying the prominent behaviors of vehicles and pedestrians, the interactions between such traffic users and the factors that influence the most, synergies between pedestrians and motorized vehicles. It is evident from the reviewed literature that studies are so far mostly focused on a limited number of factors influencing driver–pedestrian interactions (e.g., speed of vehicle, road geometry) and investigate their impact on behaviors and decision-making processes of both pedestrians and drivers. Furthermore, the effect of communication methods and intention propagation are usually studied by focusing on specific strategies (yielding behaviors or non-yielding behaviors) without taking into account the decision-making process of road users and investigating the factors that may influence the process. However, the reviewed literature showed that road users adopt their crossing strategies by considering a broad range of factors knowingly (such as estimation of time and distance gap) or unknowingly (such as influence of age or gender), while they employ different communication techniques to ease the interaction when it is needed. This shows the complexity of the vehicle–pedestrian interaction, in which solely consideration of some factors or communication methods may not provide a consummate understanding of the process. This becomes crucial for the design of emerging technologies such as ADS, requiring an accurate comprehension of human road users' behaviors in a traffic interaction to correctly predict their reactions and fulfill their expectations. With the purpose of advances in vehicle–pedestrian safety, the consideration of those interactions from ADS and the enhancement of existing infrastructure, a holistic approach is oddly yet to be considered by researchers with regards to modeling interactions of pedestrians with vehicles. However, for example, the authors in [141] have introduced a novel data-set to analyze the pedestrian behavior in interaction with vehicles by taking into account a wide range of behavioral, contextual, and dynamic factors, as from the authors' point of view sole consideration of dynamic variables (such as speed or trajectory) is not sufficient enough for prediction of pedestrians behaviors. Such an approach emphasizes even more the necessity of a vehicle–pedestrian interaction framework for a better perception of users' behaviors. Based on the findings of the reviewed literature, Figure 5 presents an example of how a holistic approach for vehicle–pedestrian interactions could be shaped.

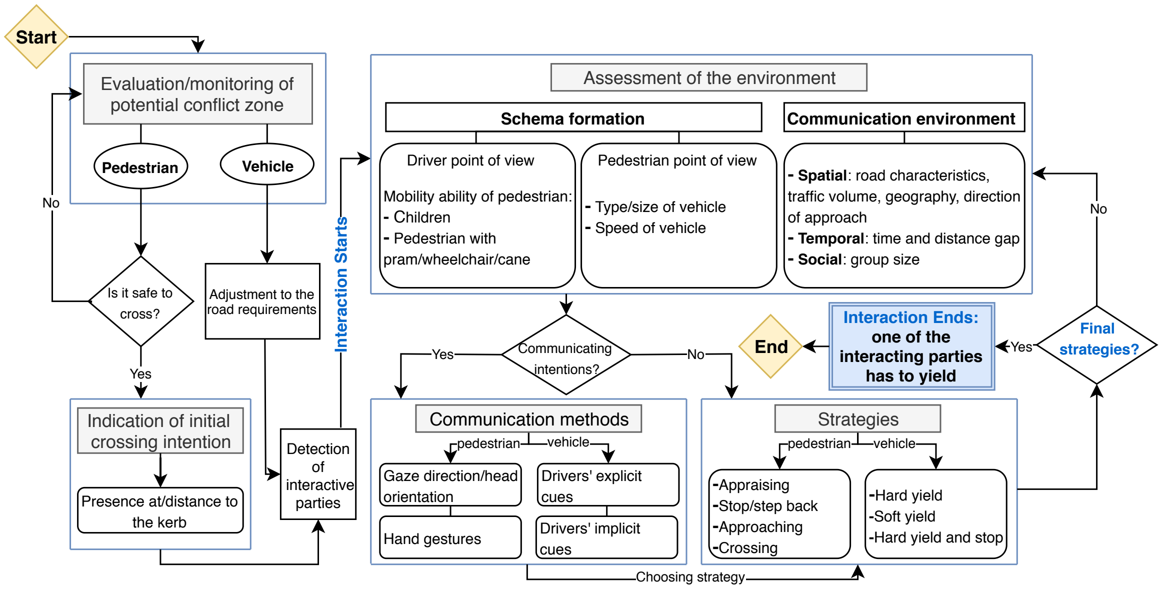


Figure 5. The simplified vehicle–pedestrian interaction process for the road crossing scenarios. Source: own elaboration, based on the reviewed references in this research.

According to Figure 5, the vehicle–pedestrian interaction can be divided into five different phases in order to simplify their decision-making process. Before forming any interaction among road users, interacting parties superficially evaluate the road characteristics on approaching the potential conflict zone. In this pre-interaction phase, a pedestrian selects the crossing point, while the drivers, on the other hand, continuously monitor the road and ideally adjust their behaviors in accordance with the road/traffic requirements. This phase is not directly involved in the vehicle–pedestrian interactions; rather, it can prepare the vehicle for an anticipatory avoidance response, rather than a delayed one on approaching a potential encountering zone. Pedestrians, then, indicate their initial crossing intentions to the users approaching the common zone, which is generally achieved through presence at or walking towards the curb. When interaction starts (the moment interacting parties detect each other), involved road users have their very first assessment about the communication environment, where they can select their strategies according to the received information and their assessment. Traffic participants can utilize communication cues to indicate their intentions or directly perform their selected crossing strategies. The interaction ends when at least one of the agents leaves the conflict zone, and can be repeated with a replaced approaching road user for the one who has not obtained the right of way. However, during the interaction, interactive agents can change their strategies or execute more than one strategy, while negotiating the right of way. Such situations generally require agents to reassess the communication environment, and communicate their new movement intentions with one another.

This holistic interaction process can provide recommendations for designing the decision-making systems of automated driving technology in confronting pedestrians. It aims at simplifying the complex decision-making procedure of pedestrians by considering the most significant factors and communication methods influencing the process. Furthermore, it could become part of the maneuvers' planning module of ADS ensuring safe maneuvering among populated spaces [142]. Finally, according to such a holistic approach, effective communication protocols and devices could be designed for faster, more comprehensive and efficient negotiations of road crossings. For example, smart-phone notifications [143], sound and optical signals [62,144], or illuminating signs [25] could provide significant help in the future for pedestrians and their corresponding actions, while on the road. Understanding the sequence of events in the vehicle–pedestrian interactions may help ADS to perform more effective communication strategies than always coming to a complete stop for pedestrians detected in their path [145]. The communication cues employed by ADS can also vary based on the environment evaluation, such as indicating visually designed eHMI instead of audible one, when the pedestrian's head is oriented towards the vehicle, or utilizing messages with the command concept rather than requesting when the pedestrian hesitates to cross.

In the present state-of-the-art, various methods have been employed to investigate the pedestrian crossing behaviors and their interaction with ADS, such as virtual reality (VR)-based simulations [146,147], the Wizard-of-Oz technique, in which the driver is hidden in the driver seat [148,149], and using the real-life exposure of automated bus shuttles [150,151]. Keferböck and Riener [152] evaluated various signs and gestures of pedestrians to explore the importance of vehicle–pedestrian interaction, and the necessity for implementation of them in the communication systems of ADS. Other studies raised relevant questions concerning the design of external communication cues, the content of communication, and the impact of different environmental factors on crossing behaviors [141,146,149,150]. Future research can potentially address pedestrian crossing behaviors and their decision-making process with respect to ADS, as a new interacting party on the road. A thorough insight into the possible changes of pedestrians' crossing-decisions while interacting with fully automated vehicles, the communication signals that pedestrians expect to receive, and the applicability of the current communication methods can be crucial for the design of ADS and thus successful deployment of such technologies. Moreover, the ubiquity of smart devices like mobile-phone, and their prevailing role in today's life of people may alter the traffic interaction concept. As distracted pedestrians are no longer an active party in the interaction process, and vehicles have to first detect such users and then react appropriately to avoid conflict. Such imperfect traffic interactions could be investigated in the future work.

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Abbreviations

The following abbreviations are used in this manuscript:

GA	Gap Acceptance
PET	Post-Encroachment-Time
TTC	Time-To-Collision
TTA	Time-To-Arrival
TAdv	Time Advantage
ADS	Automated Driving System
MUTCD	Manual on Uniform Traffic Control Devices
eHMI	External Human–Machine Interface
VR	Virtual Reality

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