Review

Interactions and Behaviors of Pedestrians with Autonomous Vehicles: A Synthesis

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Abstract: Integrating autonomous vehicles (AVs) into public roads presents profound implications for pedestrian safety and the broader acceptance of this emerging technology. This work examines the complex interactions between AVs and pedestrians, a dynamic influenced by the variability of pedestrian behaviors and the absence of traditional communication mechanisms, such as eye contact and gestures, commonly relied upon in human-driven scenarios. Given the nascent stage of AV deployment, this research addresses the challenges of evaluating AV−pedestrian interactions amid safety concerns and technological limitations. We review and synthesize global research on pedestrian behavior in the context of AV technology to track changes in pedestrians' acceptance over time and identify the factors driving these shifts. Additionally, this review incorporates insights from transportation authorities to highlight potential safety issues and the need for innovative communication strategies that ensure safe interactions between pedestrians and AVs. By analyzing these factors, the research aims to contribute to the development of guidelines and communication protocols that enhance pedestrian safety and facilitate the integration of AVs into urban environments.

Keywords: autonomous vehicles; pedestrian behavior; AV−pedestrian interaction; gap acceptance; human–machine interface; ethical perspective

1. Introduction

The market for autonomous vehicles (AVs) is projected to expand to USD 21 billion by 2035 [1]. With AVs poised to become commonplace on public roads, they will soon share urban spaces with traditional road users [2]. This imminent introduction of AVs has sparked significant research interest within the transportation sector [3]. The potential of AVs to reshape urban infrastructure and the dynamics of transportation systems is immense. Existing assistive technologies, such as lane-keeping and adaptive cruise control, which are already implemented in new vehicle models, are expected to progressively evolve into fully autonomous systems. This evolution will gradually transfer all aspects of navigation and vehicle control from human drivers to automated systems [4,5]. The societal benefits of AVs are substantial, promising reductions in crashes, enhancements in traffic efficiency, lowered congestion, and increased road capacity. According to the US National Highway Traffic Safety Administration, human error contributed to 94 percent of serious crashes in 2016 [6], many of which could be prevented by reducing human errors through autonomous driving technologies [7]. Researchers advocate that AVs could significantly increase road safety by more accurately sensing and predicting the behaviors of other road users and by eliminating risks such as driver intoxication and fatigue. Although AVs will not eliminate vehicle collisions entirely, they are expected to significantly reduce their occurrence. This research, therefore, holds significant importance in understanding and addressing the implications of AVs regarding pedestrian safety and urban infrastructure.

AVs are anticipated to maintain an environment akin to human-driven vehicles; however, current societies and autonomous driving technologies have yet to adapt fully to

the existing transportation system [8]. Safety remains the primary concern that restricts integrating AVs without human drivers into mainstream roadways [9]. It is crucial that AVs and pedestrians have transparent, socially acceptable, and efficient interactions. There is a need for uniform communication standards to foster acceptance and ensure safety. AVs should signal their intentions through symbols, text, or sounds, taking into account individuals with sensory impairments. These signals should align with the Manual on Uniform Traffic Control Devices (MUTCD), which sets guidelines for road signs, signals, and markings [10,11]. To avoid confusion and potential risks, these communication methods must be standardized across all AVs. This emphasizes the need to develop communication protocols that are easily recognizable and maintain the prescribed meanings of the MUTCD, ensuring that these new technologies do not undermine clarity and safety [11].

Recent research has emphasized the pivotal role of vehicle kinematic cues, such as speed and trajectory [12], in pedestrians' assessment of vehicular intent, which appears to influence their decision-making processes more than traditional driver signaling. Studies, such as those by Rasouli and Tsotsos [13], demonstrate that pedestrians often rely on a vehicle's dynamic motion and positioning to predict its future actions rather than on explicit signals from the driver [13]. This reliance on kinematic cues becomes even more critical in interactions involving AVs without any drivers, where conventional driver−pedestrian communication channels, like eye contact and hand gestures, are absent. Integrating these insights, it becomes apparent that designing AVs to communicate intent through understandable and predictable kinematic patterns effectively is essential for ensuring pedestrian safety and facilitating smoother integration of AVs into the urban traffic ecosystem. Therefore, enhancing our understanding of how pedestrians interpret these cues can provide crucial guidelines for developing driverless AV communication protocols that align with human expectations and behaviors.

1.1. Problem Statement

Humans naturally interpret others' intentions through body language. On the road, pedestrians need to grasp a driver's intentions, which are facilitated by traditional communication methods such as hand gestures, eye contact, and body movements. For instance, a pedestrian's posture can signal whether they are about to cross the road or are pausing for an approaching vehicle. Similarly, a driver must understand a pedestrian's intentions to ensure safety, particularly in urban settings where numerous interactions take place. The dynamic between pedestrians and AVs presents a challenge due to the absence of direct human interaction. Typically, pedestrians rely on making eye contact, using hand signals, or verbal communication with drivers to cross streets safely. In scenarios involving human drivers, these intentions are conveyed through active signaling [14]. However, with autonomous vehicles lacking a human driver, the traditional modes of interaction are missing. This absence of human elements in communication with AVs could lead to unpredictable pedestrian behaviors.

On the other hand, studies have shown that these signals are necessary for smooth traffic cooperation and safety [15]. The critical role of pedestrian interpretation of vehicular intent, particularly in the context of AVs, cannot be overstated in ensuring road safety. While AVs may be engineered to optimize stopping times and adhere strictly to road rules, pedestrians' ability to interpret these actions accurately is crucial for their safety. Misinterpretations can lead to hazardous situations, underscoring the need for AVs to communicate their intentions in a manner that aligns with pedestrian expectations and understanding. Research indicates that even perfectly performing AVs face limitations in emergency braking scenarios, which can only be mitigated by ensuring that pedestrians correctly read and react to the vehicle's behaviors [13]. Therefore, enhancing pedestrian comprehension of AVs' intents supports pedestrians' safety and reinforces AV technologies' overall effectiveness in mixed-traffic environments. This highlights an urgent research need to explore and develop more intuitive and universally understandable AV−pedestrian communication methods.

1.2. Current Gaps for Interacting Pedestrians and AVs

The study of pedestrian and autonomous vehicle (AV) interactions is an evolving field, yet several gaps warrant further exploration. One significant gap is the limitation of real-world data. Empirical data on pedestrian−AV interactions is scarce, primarily due to the limited deployment of AVs on public roads. This scarcity results in a reliance on simulated environments or controlled field studies, which may not fully capture the complexities of real-world behaviors [16]. Understanding how pedestrians perceive and respond to AVs' intentions is crucial, especially given the absence of implicit communication cues, such as eye contact and gestures, traditionally used in interactions with human-driven vehicles [5]. Pedestrian behavior in response to AVs is poorly understood, making it difficult to model and predict interactions accurately. The unpredictability of human actions, combined with the novel presence of AVs, adds another layer of complexity [12]. Ethical and legal considerations also pose significant challenges. The ethical implications of AV decision-making in critical situations, such as prioritizing pedestrian safety over passengers, are underexplored [17]. Additionally, legal frameworks for liability in AV-related incidents are still developing, creating uncertainty in regard to accountability [18]. Another gap lies in understanding the diverse interaction environments. Interaction dynamics vary significantly based on urban infrastructure, traffic density, and cultural factors [15]. Comprehensive knowledge of these variations is crucial for developing AV systems that can operate safely in diverse environments. This highlights the need for further research to address these gaps and enhance the safety and efficiency of AV integration into urban settings.

1.3. Aim of the Research

- The primary objective of this review is to explore the latest advancements in methods and techniques for understanding pedestrian crossing behavior and their interactions with autonomous vehicles (AVs) without any driver. This synthesis addresses key questions regarding current practices and innovations in pedestrian dynamics to enhance safety and improve interaction outcomes. By examining these advancements, the review seeks to provide insights that can inform future research and development in pedestrian−AV interactions.
- How is pedestrian behavior currently measured and modeled? Is this transferable to interactions with AVs?
- Are pedestrians ready to confront AVs on the road?
- What are the ethical aspects of AVs?

1.4. Structure of the Research

The following section outlines the methodology of this research, detailing the chosen approaches, tools utilized, and metrics for evaluation. It also provides an overview of the latest state-of-the-art methods for estimating pedestrian behavior. The following section discusses pedestrian road-crossing behavior. Subsequently, pedestrian interactions with AVs are discussed, and the ethical aspects of AVs are also analyzed in this section. Lastly, a discussion and conclusion section identify research gaps in this research domain. Finally, this section gives an outlook on possible future developments.

2. Methodology

A thorough literature review was conducted following Webster and Watson's [19] two-stage strategy to understand pedestrian behavior in driverless AVs' presence. The initial phase cast a wide net across various scientific databases, including ProQuest, Inspect in Engineering Village, CiteSeer, IEEE Xplore, and Google Scholar. The search, tailored with a carefully chosen set of keywords, spanned publications from 2005 to 2024. The keywords used included "autonomous vehicle", "pedestrian interaction", "safe gap", "AV technology", "pedestrian behavior", "crossing decisions", and "implicit communication". Exclusion terms were also applied to filter out unrelated studies, ensuring a focus on the

most recent and relevant research efforts. This extensive search yielded an initial pool of 431 articles, capturing the breadth of the discourse on AVs and pedestrian dynamics.

A rigorous manual screening process was then applied to refine the collection. Titles, abstracts, and authors' details were reviewed and organized. This curation process led to the exclusion of 309 articles that were either duplicates or did not meet the stringent criteria of relevance. The remaining 163 articles underwent a phase of scrutiny in which each paper was assessed for its contribution to the expanding narrative of AV−pedestrian interactions (see Figure 1). The selected articles were critically reviewed to piece together a comprehensive story of technological evolution, human behavioral patterns, and the unfolding ethical and infrastructural landscape.
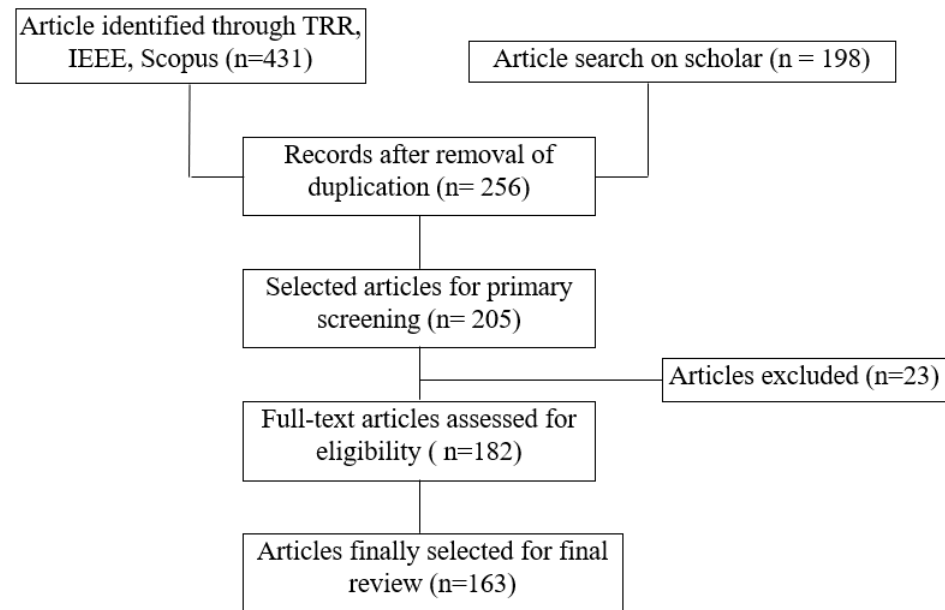
Figure 1. Article search methodology.

The review highlights the current gaps in studying the interaction between pedestrians and AVs, emphasizing the importance of simulation studies and their opportunities. Specifically, the literature revealed a notable gap in understanding pedestrian behavior at roundabouts in the context of AVs. This aspect is critical, as roundabouts present unique challenges and interactions compared to signalized intersections. Citing recent studies, such as those by Golchoubian et al. (2023) [20] and Zhou et al. (2021) [21], the review underscores the necessity for future research to delve into this area.

Furthermore, the review identifies future research directions, including the need to explore the role of explicit versus implicit communication in pedestrian−AV interactions. This is particularly important, as the literature suggests a diminishing role for explicit communication, such as eye contact and hand gestures, in favor of more implicit cues. The potential for external human-machine interfaces (HMI) to facilitate pedestrian crossing decisions is also discussed, with reference to relevant studies by Dey et al. (2020) [22]. This comprehensive review establishes a robust foundation for future research by outlining the present state of AV technology and pedestrian safety. It highlights the importance of addressing current gaps, particularly in simulation studies and roundabout interactions, and sets the stage for subsequent studies to advance the field. The review's insights are crucial for developing strategies for the harmonious integration of AVs into urban transport systems, ultimately enhancing the safety of all road users.

3. Pedestrian Behavior Estimation

Numerous studies have concentrated on developing algorithms to predict pedestrian intentions to cross roadways [23–27]. This task presents considerable challenges due to

the unpredictable nature of pedestrian movements [28,29], which are critical for ensuring the safe operation of automated vehicles. Notable contributions include a stereo-vision system by Keller et al. [30] that enables AVs to execute evasive maneuvers, as well as an assessment by Roth et al. [31] of pedestrian and driver awareness to gauge potential collision risks. Extensive research has been carried out on pedestrian detection methods [28–31], predominantly using image data [32,33], 3D points clouds [34,35], or a combination of both [36,37].

Estimating pedestrian intentions is particularly complex due to the uncertainties surrounding their next moves [38]. Pedestrians can move in various directions or stop abruptly [38,39], and their activities, such as talking to others, texting, or using their phones, add to their unpredictability. Völz et al. [40] noted that non-critical situations have not yet received significant attention. Quintero et al. [41] observed that the effectiveness of an intervention might hinge on a brief moment within seconds. As suggested in [23,41], predictive models integrate pedestrian path predictions with intention estimation. Shirazi and Morris [42] discuss pedestrian, driver, and vehicle behaviors at intersections and shed light on distinctive pedestrian motion patterns.

Research on pedestrian behavior encompasses both short-term and long-term predictions. Long-term studies frequently employ static cameras to anticipate pedestrians' ultimate destinations or travel paths [43–47]. For example, Karasev et al. [43] applied a Markov decision process in their model, concentrating on individual pedestrians while disregarding their interactions with other traffic participants. Kitani et al. [44] predicted future pedestrian actions using visually noisy data, considering the physical environment's influence on behavioral choices. Conversely, short-term models [25,26] estimate a pedestrian's location up to 2.5 s ahead, incorporating factors such as head orientation and body movement [48].

The study of human body movement is crucial in various fields, such as traffic analysis, gaming, animation, and sign language interpretation [49]. Vision-based research is dominant in this area. Numerous studies have investigated body language [22], contours [24], and postures [50] to understand pedestrian intentions. Hariyono and Jo [51] utilized a neural network to predict actions like walking, bending, starting, and stopping at crosswalks, focusing on pose recognition, lateral speed, orientation, and scene comprehension. Quintero et al. [52] employed a Gaussian Process (GP) model to reduce the dimensionality of 3D coordinates in pedestrian body poses, enhancing the understanding of dynamic movements such as walking and stopping. They also used Gaussian Process Dynamical Models (GPDMs) to forecast pedestrian intentions over a one-second horizon, though the model required over four seconds for accurate predictions [22]. Köhler et al. [24] applied a HOG-like descriptor in combination with a Support Vector Machine (SVM) to detect and interpret pedestrian motions. Furuhashi and Yamada [50] analyzed data from static cameras to predict pedestrian crossing intentions based on postural changes.

Research indicates that pedestrian decision-making is influenced by social norms within shared spaces [53–62]. Zhu and Sze (2021) [63] analyzed pedestrian behaviors at crossings through video surveys, using random parameter logit regression to assess various influences such as demographics and traffic conditions. Soathong et al. (2021) [64] conducted on-site surveys to explore perceptions of risk and convenience associated with crossing at mid-block, linking these behaviors to gender-based variations in response to social and behavioral norms. Bendak et al. (2021) [65] gathered data from urban and mid-block crosswalks, observing that pedestrians often cross quickly without looking for oncoming traffic, especially when alone or in small groups. Arellana et al. (2020) [66] explored how using virtual reality in surveys could enhance the understanding of environmental and social dynamics, noting that such immersive techniques helped participants better grasp the complex attributes of urban crossing behaviors. These studies highlight the critical role of social norms [58] and environmental awareness in pedestrian interactions and decision-making processes.

Pedestrian behavior differs markedly across various cultural contexts, affecting the overall safety of road users. Solmazer et al. (2020) found that pedestrians in countries like Turkey and Russia are more prone to risky behaviors, such as crossing against traffic signals or crossing in areas without designated pedestrian crossings [67]. These behaviors are less common in countries like Estonia, where pedestrian fatality rates are lower. Deb et al. (2017) noted that cultural norms and the enforcement of traffic laws significantly influence pedestrian behaviors, with stricter enforcement being linked to safer practices [68]. In the United States, self-reported lapses and aggressive behaviors among pedestrians correlate with higher injury severity in crashes, suggesting that intentional violations and inattentive behaviors increase pedestrian risk [6,69]. Understanding these behavioral patterns is essential for developing effective interventions and policies to enhance pedestrian safety in various traffic environments.

Regional differences in pedestrian behaviors are well documented. Rosenbloom et al. (2004) conducted an observational study in Israel, comparing pedestrians in ultra-orthodox and secular areas in regard to five behaviors: running a red light, crossing without a crosswalk, walking along the road, failing to check for traffic before crossing, and taking a child's hand when crossing. They found higher violation rates in ultra-orthodox areas compared to secular ones [70]. Similarly, a study found that Iranian pedestrians scored higher in transgressions than Pakistani pedestrians, while Pakistani pedestrians scored higher in attention violations and aggressive behaviors [71]. McIlroy et al. (2019) compared pedestrian behaviors in six countries (Bangladesh, China, Kenya, Thailand, the UK, and Vietnam), finding significant differences in violations, lapses, and aggression [67].

Papadimitriou et al. (2012) reported that 25% of Estonian pedestrians occasionally or frequently ignored red lights compared to 44% in Greece. Additionally, 41% of Estonian pedestrians crossed at non-pedestrian crossings, versus 76% in Greece. In Turkey, about 30% of participants occasionally or frequently violated pedestrian traffic rules, with around 70% rarely engaging in lapses [70]. Approximately 40% of participants never displayed aggressive behaviors, while 60% frequently exhibited positive behaviors [71,72]. These studies highlight the substantial variations in pedestrian behaviors across different countries.

4. Pedestrian Road Crossing Behavior

Perceived risks among pedestrians when encountering AVs may differ based on demographic elements like age and gender [46,47,69,73–75], further influenced by environmental and social cues that affect their decision to cross. In an investigation conducted during live demonstrations of automated pods across European cities, Merat, Louw, Madigan, Wilbrink, and Schieben (2018) utilized a questionnaire to gather insights from various age groups [73]. This study assessed safety perceptions related to interactions with automated pods in shared spaces and examined the types of information that participants deemed crucial for external display on the pods. Findings revealed a preference for designated lanes over shared spaces, with most pedestrians feeling they should have precedence over AVs in mixed-use areas. Additionally, group dynamics and social norms were noted as significant factors influencing pedestrians' willingness to take risks.

Research by Yagil [76] suggested that pedestrian adherence to laws is affected by the observed behaviors of others. Razmi et al. (2020) [77] found that factors such as proximity to an approaching vehicle, age, familiarity with AV technology, and interactions between pedestrians and AVs heavily influenced crossing decisions. Lefkowitz et al. [78] observed that the tendency to imitate others is influenced by the appearance of fellow pedestrians, with more fashionable attire leading to greater imitation. Conversely, Dolphin et al. [79] identified that smaller group sizes resulted in higher imitation rates.

Heimstra et al. [80] noted that children often cross streets in groups, with over 80% of observed instances involving collective crossing, making pedestrians less cautious and more likely to accept smaller gaps between vehicles [81]. Merat et al. [73] and Hulse et al. [74] suggest that various factors, including age, gender, AV familiarity, law compliance, geographic context, and social norms, can influence the perceived risk associated with AVs.

Shifting focus from how vehicle communication affects pedestrian behavior, this section comprehensively explores the factors impacting pedestrian actions and their interactions with vehicles.

4.1. Perception of a Pedestrian Gap Acceptance

Decision-making during road crossing is significantly shaped by a pedestrian's cognitive ability to judge a safe gap, which varies individually rather than being a uniform measure. Crossing depends on each person's critical threshold [82,83]. This behavior differs from one individual to another and is shaped by age and social demographics. For instance, older individuals typically walk slower and, along with family or friends, prefer longer gaps, whereas groups of strangers are more likely to take risks. However, Shaaban et al. (2021) [84] observed that, on a six-lane road, males and groups (platoons) are more likely to choose smaller gaps. Notably, familiar groups, such as friends or family, are less inclined to take risks, opting for more significant gaps.

Soathong et al. (2021) [64] suggested that goal-oriented habits or past experiences influence gap acceptance. Pedestrians are more likely to take risks if it means they can cross more quickly, with age playing a significant role in these decisions. For instance, children often lack an accurate perception of safe gaps and are quicker to disregard rules compared to adults [85,86]. Their unpredictable behavior makes them more difficult to predict [87]. Similarly, due to diminished cognitive abilities, older adults require more time to assess their surroundings and exhibit more cautious behavior when crossing. They tend to evaluate traffic more carefully before making a crossing decision [50] and generally have a slower walking pace than younger pedestrians [88].

Turner et al. [12] indicated that the physical limitations of elderly pedestrians hinder their ability to accurately gauge traffic conditions and the speed of oncoming vehicles, which often results in difficulties when negotiating curbs and excessive start-up times at curbsides. Additionally, the perception of a safe gap can vary by gender [80]. Research into pedestrian behaviors has generally found that female pedestrians are more cautious than males when crossing streets [87]. Typically, females exhibit lower risk-taking behaviors and higher adherence to traffic regulations [89]. Incidences of unsafe crossings are reported more frequently among both genders, yet studies also show that behavioral differences between genders are primarily attributed to distinct beliefs, motivations, and contextual factors [76,83,90]. Yagil [76] noted that male pedestrians' decisions to cross are often driven by the perceived benefits of adhering to traffic laws (normative motives). In contrast, female pedestrians are more influenced by the perceived dangers associated with crossing (instrumental motives). Further studies, such as those by Tom and Granié [89], have analyzed pedestrian visual search patterns before crossing, highlighting gender-specific differences in how crossing decisions are made. These findings suggest that male pedestrians often base their decisions to cross on immediate vehicular activity. At the same time, females are more likely to consider broader environmental elements, such as road layout, traffic signals, and the presence of other pedestrians. Despite these insights, Yagil [76] found no significant gender differences in behavior related to external situational factors, such as traffic volume, adverse weather conditions, or the presence of other pedestrians. The cumulative findings from various studies underscore that factors influencing pedestrian behavior extend beyond age and gender, including how individuals visually perceive their environment. For instance, moving pedestrians perceive safe gaps (regarding vehicle speed and distance) more accurately than those standing or waiting.

4.2. Surrounding Environment Perspective

Pedestrian decision-making before crossing a street involves processing multiple sources of information, including environmental and social cues. Factors affecting their decisions include vehicular traffic, infrastructure like streetlights and road markings, and the presence of other pedestrians. For instance, pedestrians tend to halt or delay crossing at uncontrolled intersections if they perceive fast-approaching vehicles [90]. Conversely,

the presence of a crowd may encourage riskier behavior, as individuals are more likely to follow the group.

The crossing speed of pedestrians can be affected by the type of road infrastructure present [91–93]. A study by Crompton (1979) observed different crossing speeds at various kinds of pedestrian crossings: zebra crossings had a speed of 1.49 m/s, whereas pelican crossings recorded a higher speed of 1.74 m/s [94]. This suggests that different road markings can affect pedestrians' perceptions of safety. According to the Manual on Uniform Traffic Control Devices (MUTCD) (2009) [95], the average walking speed for specific groups is set at 1.22 m/s. This standard is used to assess the adequacy of crossing intervals at traffic lights and to determine if additional time is needed for slower pedestrians by pressing the button [96,97].

Moreover, pedestrian crossing speeds vary across different regions. For example, research indicates that the average speed at which pedestrians cross at intersections and mid-block in Melbourne, Australia, is 1.53 m/s [98], while, in Jordan, it is 1.34 m/s [99]. In Malaysia, the speed at a non-signalized crosswalk averages 1.39 m/s [100], and, in Turkey, the regulatory design speed is 1.4 m/s, as per the Turkish Standards Institution [101].

4.3. Effect of Traffic Density

Extensive research has explored how pedestrians evaluate the safety of crossing streets based on dynamic elements such as the speed, direction, and proximity of oncoming vehicles [21,92,102]. The number of approaching vehicles also influences pedestrian behavior; when more than three vehicles are approaching, pedestrians tend to limit their movements [103]. Assessing vehicle speed and distance is crucial, as these factors are used to calculate the Time to Collision (TTC), a metric that estimates how long it would take for a vehicle to reach a pedestrian if it continued at its current speed [86]. Studies typically find that the average gap acceptance for pedestrians is between 3 and 7 s [86]. This acceptance varies depending on individual demographic and cultural factors [21,86]. The ability of pedestrians to judge vehicle speed and distance plays a critical role in their crossing decisions, with difficulty increasing as vehicle speed increases [104]. Sun et al. (2015) [105] discovered that pedestrians could accurately estimate the speed of vehicles traveling at or under 45 km/h, but this accuracy decreased as vehicle speeds approached 65 km/h. Moreover, other characteristics of vehicles, such as their size and type, also affect pedestrian behavior. Das, Manski, and Manuszak (2005) [106] found that pedestrians are more reluctant to cross in front of large, heavy-duty vehicles than in front of smaller passenger vehicles, largely due to challenges in judging the speed and distance of larger vehicles [107]. Additionally, the type of vehicle impacts how pedestrians judge gaps and their waiting times. Caird and Hancock (1994) [107] noted that pedestrians are quicker and more accurate in assessing gaps for motorcycles and vans than for larger commercial vehicles. This compilation of studies highlights the significant impact of vehicle−pedestrian interactions on pedestrian decision-making regarding when and where to cross the road safely.

4.4. Road Infrastructure Design Perspective

Structured road infrastructure, such as pedestrian streetlights and marked crossings, plays a crucial role in shaping pedestrian behavior in traffic settings [46,57,91,92]. Efforts to enhance traffic infrastructure are designed to reduce the risk of collisions [108]. Nevertheless, pedestrian and vehicle interactions persist in signalized zones, where some pedestrians opt to cross against the signals [109]. Infrastructure design varies in its impact on traffic flow: traffic at signalized junctions is regulated by lights that govern the flow, whereas, at zebra crossings, vehicles yield only when pedestrians make their presence known [110]. Pedestrians exhibit greater vigilance at unmarked crossings compared to signalized junctions, where their attentiveness may wane [86,111].

Road design also affects pedestrian walking patterns and trajectories. Research indicates that pedestrians are more prone to jaywalking at unmarked junctions, while they generally comply with crossing regulations at signalized intersections [92,111]. Street width

also influences pedestrian behaviors; narrower streets typically result in shorter pedestrian gap times, whereas wider streets tend to encourage jaywalking [21,86,109]. Roundabouts require AVs to navigate complex, continuous traffic flows without signal controls, making real-time decision-making and advanced sensing critical for pedestrian safety. Research indicates that, while roundabouts can reduce vehicle speeds and potentially enhance safety, the integration of AVs introduces new challenges and opportunities for improving pedestrian−vehicle interactions through advanced technologies and infrastructure design; the integration of AVs necessitates further study on how these vehicles interpret and respond to pedestrian behaviors at these intersections [112]. Moreover, pedestrian walking speed varies depending on the road structure, with individuals walking faster on crosswalks than on sidewalks [21,113]. Lighting levels further impact the movement of vehicles and pedestrians. Specifically, during night-time, reduced illumination impairs pedestrians' ability to accurately judge traffic risks, prompting more cautious behavior [105]. The behavior of pedestrians on unregulated roads contrasts with that on regulated roads and junctions, underscoring an uncertainty as to whether pedestrians consistently yield or assert their right of way during encounters with drivers.

4.5. Exploring Pedestrian's Risky Behaviors

Extended waiting times at intersections significantly affect pedestrian crossing decisions. Sun et al. (2003) [114] noted that prolonged wait times tend to increase risk-taking behaviors among pedestrians. Additional research has highlighted that demographic factors and individual personality traits also influence how long pedestrians wait and when they decide to cross [115]. Moreover, as outlined in Sections 4.1 and 4.2, it is clear that a variety of factors beyond mere risk-taking tendencies influences pedestrian crossing decisions. Conflicts between drivers and pedestrians often arise from the behavior of both parties within traffic operations [21,116]. The inherent risk of collisions typically keeps pedestrians on sidewalks, yet this behavior can vary widely across different locations and cultures [117]. For instance, pedestrians in Manhattan are known to assert their right of way at unmarked crosswalks and often cross ahead of vehicles. In contrast, in places like Miami, pedestrians tend to be more cautious due to drivers' frequent disregard of traffic rules [98].

Conversely, in crowded areas, drivers often adapt to the unpredictability of pedestrians by modifying their speed and driving behavior. Regarding autonomous vehicles (AVs), pedestrians tend to trust these vehicles' actions less. Recent studies involving human subjects have indicated a reluctance to cross in front of self-driving vehicle prototypes [118], although other studies have shown a mix of risk-taking and cautious behaviors in such situations [20]. The perception of a safe gap in traffic varies among individuals. Analytical studies on risk assessment in pedestrian crossing behaviors have revealed notable patterns in waiting time distributions. According to Li [119], the waiting times for a mixed group of risk-taking and risk-averse pedestrians typically follow a U-shaped distribution, indicating that risk-takers become impatient with prolonged waiting, while risk-averse individuals are less likely to cross as their wait extends [120]. However, the latter's reluctance diminishes if they see others beginning to cross. Faria et al. [121] suggest that groups of pedestrians may engage in riskier crossing behaviors under such influences.

5. Pedestrian's Interactions with Autonomous Vehicles (AVs)

The emergence of autonomous vehicle (AV) technology raises questions about its impact on pedestrian behavior and pedestrian interactions with these vehicles [111]. Typically, eye contact between pedestrians and drivers increases the likelihood of vehicles yielding [122]. Nathanael et al. [123] observed in their naturalistic study that a pedestrian merely turning their head towards a vehicle was sufficient for drivers to confidently gauge the pedestrian's intentions, occurring in about 52% of interactions. However, mutual eye contact between drivers and pedestrians happened in only 13% of cases, with explicit signaling being noted in just 2% of interactions. Pedestrians often intend to cross the road and

use various signals, such as eye contact or gestures, to communicate their intentions [16]. Human drivers can usually interpret these cues and respond accordingly [86].

Simulation studies play a critical role in AV−human interactions. They provide a controlled environment where various scenarios can be tested without the risks associated with real-world experiments. This is particularly useful for studying rare but critical situations like emergency braking or complex roundabout interactions [112]. Advanced simulation tools can incorporate detailed models of pedestrian behavior, allowing researchers to observe how pedestrians might react to different AV behaviors and communication methods [41]. Additionally, simulations enable testing a wide range of scenarios, including those that are difficult to recreate in real life, such as varying traffic densities, different weather conditions, and the presence of other road users. This capability allows for a comprehensive evaluation of AV systems under diverse conditions [124]. The iterative nature of simulation studies also facilitates the continuous testing and refinement of AV algorithms and communication protocols, ensuring they are robust and effective before deployment on public roads. They provide a safe and controlled means to explore complex scenarios, refine AV technologies, and ultimately contribute to safer and more effective integration of AVs into urban environments.

However, interactions between pedestrians and autonomous vehicles (AVs) can lead to incorrect crossing decisions due to perception or comprehension challenges, as pedestrians might struggle to distinguish between human-driven vehicles and AVs [2,125]. Decoding informal traffic language remains a significant challenge for AVs. Even when a human driver is present in an AV, they may not be attentive to the road and could be engaged in other activities, such as reading a newspaper [2,126], which complicates communication attempts between pedestrians and drivers. Furthermore, cultural variations in the informal communication used by road users can further complicate the decision-making processes of robotic vehicles.

5.1. Intent Perception and Communication

The psychological factors influencing pedestrian crossing decisions are complex [50,53,88,116]. Research shows that pedestrian demographics, social dynamics, and traffic conditions play a significant role in shaping crossing intentions [13,111,125]. However, interactions with AVs may prompt different behaviors compared to traditional vehicles [111]. Accurately predicting pedestrians' intentions is essential for AVs to anticipate pedestrians' potential movements [125]. A significant challenge for future vehicles lies in integrating diverse contextual information into algorithms that estimate pedestrian intentions [127]. Conversely, it is crucial for the vehicle's intentions to be clearly communicated to pedestrians. Thus, developing an effective communication method to convey the vehicle's intentions to human road users represents another challenge [128]. A quasi-experiment by Gueguen et al. [122] demonstrated that pedestrian behavior at intersections is significantly influenced by whether or not they make eye contact with drivers. Pedestrians adjusted their behavior based on whether they perceived a vehicle as automated, with some participants stopping in their tracks upon noticing an AV.

Rothenbücher et al. [129] conducted experiments using a "ghost driver" platform, where a human driver was hidden inside a seat suit in a car labeled as an automated vehicle. The results indicated that this mock automated vehicle did not alter pedestrians' interactions or crossing behaviors, provided that the vehicle behaved predictably at pedestrian crossings and roundabouts. Participants reported having lower expectations of autonomous vehicles compared to human drivers. One participant expressed concerns about increased risk due to the lack of a visible driver, stating discomfort when crossing in front of the vehicle. Additionally, a study by Rodríguez Palmeiro et al. [2] found that while pedestrians' willingness to cross in the presence of Wizard-of-Oz AVs—where drivers were distracted or the vehicle was marked as self-driving—did not change, their crossing behaviors were modified.

5.2. Autonomous Vehicle Visual Signals Concepts

Visual cues have traditionally served as signals on traditional vehicles to convey driver intentions. Similarly, within the automotive realm, there is a growing acceptance that AVs can utilize visual cues to communicate their intentions. Several researchers have proposed conceptual solutions for enhancing communication between AVs and pedestrians, suggesting the use of displays, lights, and projectors [130]. Lagstrom and Lundgren [131] explored a video-based approach, incorporating LED strips arranged in different sequences to indicate various vehicle modes (e.g., LED strips contracting towards the center to show the vehicle is about to start or expanding towards the sides to indicate it is about to yield). Their findings revealed that pedestrians quickly understood these signals after minimal training, replacing the informal communication style of human drivers with more transparent and immediate notifications.

However, without prior training, these features may not convey messages about the vehicle's intentions that are easily understandable to the general public. In a study conducted in 2016, Deb et al. [68] conducted an online survey involving 182 participants to explore pedestrians' expectations regarding the external features of AVs, including both visual and auditory elements, and sought participants' suggestions. Most respondents preferred visible indicators, such as a 'walking pedestrian sign' or a 'timer clock', to indicate the vehicle's intention to halt at a crosswalk. Additionally, participants recommended incorporating audible interaction features to cater to distracted and visually impaired pedestrians.

In a survey conducted by Fridman et al. [132], 30 different design interfaces for various states of an autonomous vehicle were tested using responses from 200 participants. Among their findings, they recommended using a green 'walk' text accompanied by a pedestrian silhouette to signal safe crossing while employing 'do not walk' in red alongside an upraised hand to halt pedestrians. However, relying solely on color may lead to confusion due to differing perspectives among road users. In another study, Clamann et al. [133] explored different designs for 'walk' and 'don't walk' signs. They concluded that pedestrians tend to base their crossing decisions on established behaviors, such as assessing the gap between themselves and vehicles and vehicle speed, rather than information presented on external displays. Notably, in this study, a human passenger was present in the driver's seat to manage any adverse situations. The presence of a human driver in an autonomous vehicle can potentially confuse pedestrians regarding the vehicle's control, potentially leading to unpredictable conditions like near-misses or collisions [117].

The authors employed a validated pedestrian simulator [134,135], Unity 3D, and an HTC Vive headset to better understand pedestrians' perceptions of AVs. Validation results from this study indicated that participants' walking speeds in the simulator closely matched average pedestrian crossing rates with human-driven vehicles. Survey responses also revealed that participants felt a strong sense of presence in the virtual environment and rated the simulator highly in terms of usability and realism [136].

5.3. Investigating Safety Measures for Pedestrians in Autonomous Vehicle Contexts

Since the inception of driver-assist and autonomous vehicle (AV) technologies, enhancing safety has remained a primary focus in numerous predictive studies [137–139]. As low-automation AVs become increasingly common on our roads, recent statistics on AV-related crashes indicate a notable improvement, particularly in crash severity [139]. However, the emergence of new data sources necessitates a more thorough examination of the safety of various road users in AV environments, with pedestrians being a notably overlooked segment of the traffic flow [95]. Despite their relatively understudied role, pedestrians are expected to engage in complex interactions with AVs, especially given their propensity for random or unexpected behaviors when navigating a mixed-traffic stream of manually driven vehicles (MDVs) and AVs, which can give rise to noteworthy conflict patterns.

Most studies focusing on AV−pedestrian interactions place considerable attention on the AV's perspective, as it is assumed to bear the responsibility for detecting pedes-

trians on the road and prioritizing their safety [136,140,141]. These studies often employ mathematical models and deep-learning algorithms to aid AVs in detecting pedestrians and anticipating their intentions at critical locations, such as crosswalks and traffic signals. However, much of the research on AV−pedestrian conflicts has relied heavily on simulation-based approaches due to the limited availability of empirical data [142,143].

Among the scarce studies that have managed to gather data on AV−pedestrian conflicts, both Dey et al. (2019) [144] and Rodríguez Palmeiro et al. (2018) [2] were confined to closed road segments. They found no statistically significant difference in pedestrian safety between AV−pedestrian conflicts and those involving MDVs. More recent efforts have addressed some challenges associated with deploying AVs on open roads by utilizing AV shuttle pods [139]. This approach has enabled investigations into actual pedestrian behavior under real-world conditions despite the unconventional shape of the pods and the dedicated lanes allocated to them. Notably, Madigan et al. (2019) [145] utilized 22 h of video data captured in Greece and France, depicting the traversal of a 2 km route by an AV pod. By combining manual and automated video analysis, the study identified general interaction patterns between AVs and road users, with pedestrians maintaining additional lateral distances from AV pods compared to other vehicles. Similarly, in Québec, Canada, Beauchamp et al. (2022) [17] conducted a similar study, utilizing 70 h of video footage to focus on traffic conflict indicators such as Time to Collision (TTC), Post-Encroachment Time (PET), speed difference, and headway. Their investigation aimed to examine interactions between AV pods and various road users. While the findings suggested that AVs exhibit safe behavior during interactions with pedestrians, concerns were raised regarding AV interactions with MDVs, where reported headways were shorter than typical.

5.4. Autonomous Vehicles and Pedestrian Trust

Pedestrians' perceptions of AVs can lead to misplaced trust and inaccurate expectations regarding their behavior. For example, if pedestrians assume that an approaching vehicle is self-driving, they might accept a shorter gap, believing that AVs will always yield. Conversely, pedestrians may choose a larger gap due to distrust in the AV's capabilities, significantly increasing waiting times. Jayaraman et al. [146] utilized the uncertainty reduction theory (URT) to explain that pedestrians' trust in an AV correlates with their knowledge of it. However, recent research in robotics trust indicates that a user's trust in a robot is not solely dependent on its performance [147] but also on their perception of its capabilities [148].

5.5. Role of eHMIs in Facilitating Pedestrian Crossing Decisions

External Human–Machine Interfaces (eHMIs) have been proposed as a solution to bridge the communication gap between AVs and pedestrians, especially in the absence of traditional explicit communication cues such as eye contact and hand gestures [149]. Research indicates that pedestrians rely more on implicit cues, such as vehicle speed and trajectory, rather than explicit signals when making crossing decisions [112,117].

This suggests that, while explicit communication has its role, it is not the primary factor in pedestrian decision-making processes. eHMIs can complement these implicit cues by providing additional layers of information that enhance the predictability and transparency of AV behavior. For instance, eHMIs can use visual signals (e.g., LED displays indicating "safe to cross") [131] or auditory cues to convey the vehicle's intentions [48], thereby reinforcing the implicit communication provided by the vehicle's movement. One of the key benefits of eHMIs is their potential to enhance safety by making AV behavior more predictable. Pedestrians often feel uncertain when interacting with AVs due to the lack of a human driver for interpreting non-verbal cues. By implementing eHMIs that clearly signal the AV's actions, such as stopping or yielding, pedestrians can make more informed decisions about when it is safe to cross [150]. This predictability reduces hesitation and confusion, potentially decreasing the likelihood of crashes. eHMIs can be particularly useful in complex traffic scenarios where implicit cues alone may not suffice.

For example, at busy intersections or roundabouts, eHMIs can provide clear signals that help pedestrians understand the AV's intended path and actions [112]. Additionally, in low visibility conditions, such as night-time or adverse weather, eHMIs can offer enhanced visibility of the vehicle's intentions, further aiding pedestrian decision-making.

Despite their potential benefits, there are challenges and considerations in implementing eHMIs effectively. One major challenge is ensuring that the signals used by eHMIs are universally understandable and intuitive for all pedestrians, regardless of age, cultural background, or familiarity with AV technology. Standardization of eHMI signals is crucial for preventing confusion and ensuring consistency across different AV models and manufacturers. The reliance on eHMIs should not overshadow the importance of designing AV systems that inherently promote safe interactions through their behavior. Overemphasis on explicit communication could inadvertently lead to scenarios where pedestrians become overly reliant on eHMI signals, potentially neglecting the importance of implicit cues. eHMIs have the potential to facilitate pedestrian crossing decisions by enhancing the predictability and transparency of AV actions [149]. They can complement implicit communication methods, providing additional safety assurances in diverse and complex traffic scenarios. However, careful consideration must be given to the design and standardization of eHMIs to ensure they are effective and universally understood. Balancing eHMIs with robust AV behavior design will be key to fostering safe and efficient interactions between pedestrians and AV [149].

6. Ethical Aspects of Autonomous Vehicles

The emergence of AVs offers different financial and societal benefits; to ensure these benefits, many challenges need to be confronted, including ethical challenges. Since human life is involved in these decision-making processes, making a moral decision in a complex situation is essential. Often, a situation may arise when a machine may decide to save a passenger or collide with multiple pedestrians [18]. For example, a situation may arise for the machine (AV) where it may need to decide if it wants to save its only passenger or kill five pedestrians. These moral dilemmas are points of concern for autonomous vehicle programmers [151]. The trolley problem [152] is an example of an ethical issue where an autonomous machine needs to decide on complicated real-world traffic crashes.

In a 2014 publication, Noah Goodall delves into the ethical considerations surrounding AVs [153]. Goodall highlights the necessity for vehicles to react swiftly in safety-critical situations, necessitating pre-programmed decision-making. Given the diverse ethical viewpoints in contemporary society, experts have disagreed about incorporating ethics into vehicle programming. Goodall further explores various facets of autonomous vehicles and the ethical dilemmas they pose. He acknowledges the widespread discussion of the "trolley problem", a hypothetical scenario presenting a choice between two morally challenging options, such as sacrificing one individual to save multiple others. However, Goodall contends that this scenario is unrealistic due to the myriad unpredictable outcomes and consequences of vehicle collisions, significantly amplifying ethical decision-making complexity.

Ethical decisions also vary from culture to culture. For example, if someone needs to drive from Vancouver, Canada, to Los Angeles, USA, the driver must pass through Washington, Oregon, California, the USA, British Colombia, and Canada. The autonomous vehicle needs to pass through various small and large cities and municipalities with different local laws, customs, and ethical practices regarding pedestrians and localities. It will become a challenge for the AV manufacturer to incorporate all the geography-dependent ethical issues [121]. Hence, moral customs need to be embedded with AV-controlling software systems [154]. Hevelke and Nida-Rümelin delve into the ethical dimensions of autonomous vehicles, particularly regarding crash scenarios [155]. They posit that the advent of AV is expected to lead to fewer and less severe crashes, a moral benefit that strengthens support for this technology. However, they also introduce the ethical theory of "trading lives", which suggests that individuals who would not have been involved in a crash without autonomous vehicles may become victims once this

technology is introduced. This ethical trade-off raises complex moral considerations. An analogous situation is observed with seat belts, widely recognized as life-saving devices but occasionally implicated in fatalities. Similarly, AVs present a comparable dilemma if crash rates are as low as anticipated.

Hevelke and Nida-Rumelin further explore liability scenarios in an autonomous vehicle environment [155]. They propose two potential liability models, one in which all users share the risk through taxation or mandatory insurance and another in which the user bears responsibility at the time of the incident. This underscores the need for a comprehensive understanding of liability frameworks in the context of autonomous vehicles. A study conducted at Stanford University in 2015 by Gerdes and Thornton endeavors to identify practical ethical frameworks for implementation in autonomous vehicles [156]. The authors conclude that no single ethical approach is ideal for programming decision-making in autonomous vehicles, advocating instead for a combination of ethical principles. They also raise the moral dilemma of human override, questioning the ethics of transferring responsibility and control to a human driver when the vehicle possesses data indicating an imminent collision. Moreover, the study emphasizes the importance of aligning autonomous vehicles' capabilities with societal expectations regarding responsibility for adverse outcomes. The only existing publication addressing an agreed-upon Code of Ethics for AV is a 2017 report by the German Ethics Commission on Automated and Connected Driving [157]. This report underscores the historical precedence of ethical concerns surrounding automated transportation systems, and it advocates for prioritizing ethical considerations in developing and deploying autonomous vehicles.

Another major concern is privacy issues associated with sharing road users' personal information [70]. Currently, five states and the District of Columbia have enacted laws addressing autonomous vehicles, but none adequately cover key areas of data privacy and security, such as the collection, use, and protection of consumer data gathered by AVs. This regulatory gap leaves consumers vulnerable to data breaches and cyber-attacks. Hackers could potentially access personal data, track vehicle locations, and even determine if a driver is home, posing significant privacy risks [158]. Moreover, cyber-attacks on AVs could have fatal consequences, threatening not just the vehicle's occupants but also pedestrians and other road users. Addressing data privacy concerns and upgrading road infrastructure are critical components of the ethical and safe deployment of AVs. Ensuring robust data protection measures and enhancing infrastructure to support AVs and vulnerable road users will help mitigate risks and promote a harmonious integration of this advanced technology into our transportation systems.

7. Limitations and Drawbacks in Modeling AV−Pedestrian Interactions

Modeling the interactions between AVs and pedestrians is a critical yet challenging aspect of urban traffic management and AV technology development. This complexity arises from the unpredictable nature of human behavior and the technical limitations of current AV systems. Modeling the interactions between pedestrians and AVs presents numerous challenges due to the intricacy of traffic dynamics and evolving road user behaviors. Song et al. (2023) highlight the necessity for pedestrians to adapt their behavior to accommodate AVs, a new road presence [158]. As AVs continue integrating into everyday traffic, the imperative grows for these systems to effectively decode and respond to the nuanced, often non-verbal communication cues traditionally used in human traffic interactions. Such advancements are vital to mitigating potential misunderstandings that could lead to confusion or traffic crashes [156].

Technological Readiness: While AV technology has advanced significantly, fully autonomous vehicles are not yet commonplace on public roads. The existing models are primarily at various semi-autonomy levels, meaning they can handle specific driving tasks but require human oversight for complex decision-making situations. This transitional phase poses challenges in predicting interactions between human-driven vehicles, semi-autonomous vehicles, and pedestrians.

Behavioral Adaptation: Pedestrians are accustomed to interacting with human drivers through subtle cues like eye contact and gestures, which help them assess the driver's awareness and intentions. AVs, however, lack these human elements, making it difficult for pedestrians to predict vehicle behavior. The absence of universally understood signals from AVs adds another layer of complexity to pedestrian decision-making processes.

Inconsistent Communication Standards: There is currently no standardized method for AVs to communicate their intentions to pedestrians, such as stopping or yielding. Different manufacturers might implement various signaling systems, which can confuse pedestrians and lead to unsafe crossing decisions. Establishing a uniform communication protocol that is easily recognizable and understood by all pedestrians is crucial.

Dynamic Interaction Environments: The environments where pedestrians and AVs interact are highly dynamic and often unpredictable. Variables such as weather conditions, traffic density, and urban infrastructure can significantly affect the behavior of pedestrians and vehicles. Modeling these interactions requires sophisticated simulation tools that can account for the myriad environmental factors impacting decision-making on both sides.

Data and Methodological Gaps: There is a scarcity of empirical data on real-world AV−pedestrian interactions, limiting the ability to model these encounters accurately. Most current research relies on simulated environments or controlled field studies, which may not fully capture the complexities of spontaneous human behavior in naturalistic settings.

Ethical and Legal Considerations: As AVs take on more driving responsibilities, questions about liability and ethical decision-making in the event of a crash become more pressing. Modeling these scenarios involves technical considerations and ethical frameworks that guide the behavior of AVs in critical situations.

Numerous unresolved queries linger within the realm of automation technology. These include identifying pivotal factors shaping pedestrian behavior, understanding their ramifications on pedestrian actions, discerning potential interrelations among these factors, and devising strategies for integrating them into autonomous vehicle (AV) technology.

8. Discussion

The primary aim of this research was to explore and analyze advancements in pedestrian dynamics and interactions with autonomous vehicles (AVs), with a focus on improving urban transport systems and pedestrian safety. Our findings indicate that, while AV technology can potentially enhance urban mobility and reduce traffic accidents, significant challenges remain, particularly in ensuring pedestrian safety in mixed-traffic environments. This study has revealed critical insights into pedestrian behavior in the presence of AVs, emphasizing the need for more intuitive communication systems that can replace traditional cues like eye contact and gestures. We found that AVs can interpret pedestrian intentions with a certain level of accuracy thanks to advanced sensors and processing capabilities. However, the absence of human-like interactions—such as acknowledgment through gestures or facial expressions—poses a significant challenge. This research has shown that effective communication between AVs and pedestrians is crucial and can be significantly enhanced by implementing external Human–Machine Interfaces (eHMIs). These systems must be designed to convey clear and understandable signals to pedestrians to ensure their safety and foster smoother integration into urban settings. Moreover, this research highlights the importance of incorporating these findings into developing urban infrastructure and traffic management policies. Integrating AVs into urban centers requires technological adaptation and infrastructural changes that accommodate both AVs and traditional vehicles without compromising pedestrian safety. Future policies should focus on creating environments where AVs and human road users, including pedestrians and cyclists, can coexist safely. This might involve redesigning crosswalks, modifying traffic signals, and, perhaps most importantly, standardizing AV communication protocols to ensure that all pedestrians can easily understand AV intentions.

8.1. Policy and Practical Implementation for AV and Pedestrian Interaction

Developing effective policies and practical implementations for AV and pedestrian interactions is crucial for ensuring safety and public trust in autonomous vehicle technology. Policymakers must establish comprehensive regulations that address key aspects of AV operations, including data privacy, cybersecurity, and the design of external Human–Machine Interfaces (eHMIs). For instance, regulations should mandate the use of standardized eHMI signals to communicate AV intentions clearly to pedestrians, enhancing safety at crossings and other shared spaces. Such standards can include visual signals (like lights or symbols) and auditory cues to indicate when it is safe to cross. Additionally, policies should enforce stringent data privacy protections to prevent unauthorized access to sensitive information collected by AVs, addressing significant ethical concerns. These protections should include robust encryption methods and strict data handling protocols to ensure that pedestrian and vehicle data are used appropriately and securely. On the practical side, integrating AV technology with existing urban infrastructures requires a multifaceted approach. Cities should invest in smart infrastructure, such as intelligent traffic management systems that utilize Vehicle-to-Everything (V2X) communication to provide real-time traffic data, improving AV navigation and pedestrian safety. Dedicated lanes for AVs can help segregate different types of road users, reducing the likelihood of accidents. Additionally, the implementation of smart crosswalks equipped with sensors and eHMIs can facilitate safer pedestrian crossings by clearly signaling AV intentions. Public awareness campaigns are essential to educate pedestrians about how to interact safely with AVs, including recognizing and understanding eHMI signals. Pilot projects and real-world testing of these technologies and policies can provide valuable insights into their effectiveness, allowing for continuous improvement. This iterative process helps adapt both policies and technologies to ensure a seamless and safe integration of AVs into everyday traffic environments. By focusing on these comprehensive strategies, cities can create an environment where AVs and pedestrians coexist safely. This approach not only enhances public safety but also builds public confidence in AV technology, paving the way for broader adoption and more efficient transportation systems.

8.2. Future Direction

Continued research is needed to explore the long-term implications of AV integration, focusing on pedestrian behavior, technological advancements, and the evolving landscape of urban traffic management. Future research should prioritize enhancing implicit communication methods between AVs and pedestrians, understanding how pedestrian behaviors adapt over time, and utilizing simulation studies to explore complex interaction scenarios. Developing ethical decision-making frameworks for AVs is crucial, ensuring that these systems can handle critical situations with moral considerations. Additionally, evolving policy and regulatory frameworks to address liability issues, standardize communication protocols, and redesign urban infrastructure will support AVs' safe and effective integration into urban environments. These efforts will improve transportation safety, efficiency, and public trust in AV technology.

The findings from this review make a significant contribution to the field by providing a clearer understanding of how AVs and pedestrians interact and by outlining the adjustments necessary in urban transport systems to accommodate emerging AV technologies. The study emphasizes the need for continuous collaboration between technologists, urban planners, and policy-makers to ensure that the integration of AVs into urban transport systems prioritizes human safety, efficiency, and public trust. Our review contributes foundational insights that will aid in developing effective strategies for the harmonious integration of AVs into society, ensuring that this transition supports the safety and efficiency of all road users. The strategic development of AV technology, grounded in ethical considerations and supported by appropriate policy and implementation adaptations, is essential for successfully integrating AVs into everyday life [111,117].

9. Conclusions

This review ventures into the nuanced dynamics of pedestrian interactions with autonomous vehicles (AVs), shedding light on the complex challenges and critical development areas as AVs become more prevalent in urban traffic systems. The disruption of traditional communication methods—eye contact and gestures—that pedestrians use to gauge vehicle intentions, which are absent in AVs, creates a communication gap. This gap in communication raises safety concerns, particularly in complex environments like near schools or hospitals where nuanced interactions are crucial [159]. This absence necessitates the development of new forms of communication that can effectively convey AVs' intentions to pedestrians to ensure safety across various urban environments. Our findings emphasize that, while AVs detect pedestrians and other vehicles, they cannot engage in nuanced human-like interactions, which are crucial in complex environments like school zones or busy urban centers. This limitation could potentially lead to safety risks if not addressed adequately. Moreover, the ethical considerations associated with deploying AVs in pedestrian-rich areas highlight the need for AVs to make decisions that align with societal ethical standards, ensuring that these technologies do not compromise human safety for operational efficiency.

In light of these insights, it becomes clear that policy and infrastructure must evolve in tandem with the advancement of AV technology. This includes redesigning traffic systems and urban infrastructures to accommodate AVs and traditional vehicles without compromising the safety of all road users. For instance, integrating smart traffic management systems that can communicate directly with AVs and other road users can significantly enhance the safety and efficiency of urban transportation. Furthermore, our review underlines the importance of continuous research into AV−pedestrian interactions, focusing on developing advanced communication interfaces and detection technologies. These technologies should find a way to mimic human interactions and anticipate pedestrian movements more accurately, thus improving the overall safety of urban transportation.

In conclusion, integrating AVs promises significant benefits, such as reduced traffic congestion and enhanced safety. The transition towards integrating AVs into urban traffic systems offers substantial benefits, such as reduced traffic congestion and lower accident rates. However, this transition also requires careful consideration of this technology's operational challenges and ethical dilemmas. Through collaborative efforts among technologists, urban planners, policymakers, and the public, we can ensure that the integration of AVs into our urban landscapes is conducted in a safe, efficient, and ethically responsible manner.

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