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PEDESTRIAN BEHAVIOR AT INTERSECTIONS: A LITERATURE REVIEW OF MODELS AND SIMULATION RECOMMENDATIONS

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ABSTRACT

Understanding the behavior of pedestrians at intersections can help to improve the efficiency and safety in urban traffic systems and has increasingly drawn the attention of the transportation industry. Pedestrian behavior and movement are of high uncertainty and difficult to analyze, not only because of the individual characteristics, but also the interaction with vehicles and infrastructures. This study specifically investigates various modeling studies on pedestrian behavior at intersections. Insights are provided regarding the inputs, algorithms, and application scenarios. Also, this study identifies limitations in the existing traffic simulation tools involving pedestrians and provides recommendations for addressing these issues in future research. The modeling and simulation of the interaction among vehicles and pedestrians at intersections are open challenges and can be used as helpful tools to boost the development of Advanced Driver Assistance Systems (ADAS) as well as intelligent intersections.

1 INTRODUCTION

About 30 percent of the traffic accidents and collisions that happened in China were intersection-related (Wang et al. 2015). Intersections are key points in the urban traffic systems which affect the efficiency and safety of vehicles as well as pedestrians. Besides, analyzing the participants’ behavior is always a popular topic in transportation studies. Vehicles and pedestrians are the fundamental components of an intersection. Pedestrians take up about 26 percent of total traffic accident fatalities globally, according to the 2018 global road safety report (WHO 2019), and they are more vulnerable and less protected compared to vehicles. To protect pedestrians, many countries have been working on establishing related traffic policies and laws to increase the share of walking as a transport mode. These policies can help to curtail the growth in car usage in the city center, where traffic congestion brings associated environmental contamination and decreases urban livelihoods. To better implement the policies, there has been a need to understand pedestrian behavior. Moreover, the development of Advanced Driver Assistance Systems (ADAS) for automated vehicles requires the ability to predict pedestrian behavior accurately to avoid collisions. However, the behavior of pedestrians is less studied compared to the behavior of drivers (Shirari and Morris 2016). There are many mature microscopic models to describe the vehicles following as well as lane changing maneuvers, while ignoring the interaction with pedestrians. In order to make intelligent cars adjust to complex urban scenarios, pedestrian behavior should be quantified and modeled.

1.1 Objective and Research Questions

There are several literature reviews on pedestrian behavior. Geronimo et al. (2009) focused mostly on pedestrian detection using computer vision algorithms for ADAS applications. Ridel et al. (2018) reviewed the pedestrian intention prediction studies in urban scenarios, while intersections are the most complicated case. More specifically, Shirari and Morris (2016) reviewed the participants' behavior and safety analysis including vehicles, pedestrians, and drivers at intersections. However, no comprehensive survey exists specifically addressing the modeling of pedestrian behavior at intersections. Also, for existing traffic simulation tools, the simulation for pedestrians at intersection scenarios is over-simplified and the effect of pedestrians is overlooked, for which simulation results may have a large variance from the real case. Thus, the objective of this study is to give recommendations about how to improve pedestrian simulation based on existing behavior models. It will be achieved by studying the existing research literature on pedestrian behavior models and simulation at intersections, concentrating on studies since 2000 with an emphasis on the interaction with the vehicular flow, to address the following questions:

1. What kinds of behaviors should be considered and what are the factors?
2. Which analysis models have been applied to describe pedestrian behavior?
3. How should existing traffic simulation tools be improved to better simulate pedestrians?

1.2 Overview of the Paper

The remainder of this paper is structured as follows: In Section 2, the method for systematic literature review is summarized. Section 3 reviews the pedestrian behavior observations to find which kind of behavior should be modeled and what are the latent factors. Section 4 surveys existing models to estimate pedestrian intentions under various situations. Section 5 comments on the simulation studies and gives recommendations for improving simulations. Finally, Section 6 summaries this study and gives insight into possible future research. The overall objective of the research is to support the development of a microscopic tool for simulating pedestrian behavior at intersections. The simulation model can help to design ADAS as well as cooperative intersections to achieve accident avoidance and efficiency improvement.

2 RESEARCH METHODOLOGY

To give an overview and to identify the structure of a broader research area, the research method for the systematic literature review is discussed. First, a database search based on Google Scholar was performed. The queries were "pedestrian behavior modeling and simulation", "pedestrian simulation", and so on, and the time range is since 2000. Second, the screen selection of papers was performed on title, abstract, and keywords. Also, the environment of the studies is confined to be at crosswalks or intersections. For those papers that appeared potentially relevant, the full papers were browsed to ascertain the fulfillment of the criterion. After building the initial set of papers, a complementary snowballing search was conducted, in which references from those papers were followed to check for additional literature. Bidirectional snowballing was done by going through the titles to identify relevant papers.

The initial searches resulted in 152 papers. After screening, 25 papers remained. Then, snowballing was applied, and 8 papers were added, leading to a total set of 33. In addition to the primary studies, the literature where the pedestrian behavior is central but has a different focus was retained and used as complimentary references throughout this paper. More than half of the reviewed papers concerned with models and simulations are published after 2015, and they are from high-quality academic journals and meetings in traffic and simulation areas. Some of the reviewed papers that are published in traffic research journals and meetings might not directly relate to simulation, but these studies focus on the intersection environment and explored the models to describe the pedestrian behavior.

3 PEDESTRIAN BEHAVIOR

To perform modeling, the first step requires collecting and organizing data from sources. An attempt is made here to present the results of various studies to provide meaningful interpretations of pedestrian behavior while noting the latent factors. In Table 1, representative papers are reviewed to gain insight into the current research on pedestrian behavior analysis at the crosswalks. To provide a succinct yet informative review, these papers are summarized. “Data Source” gives the data used in the study. “Description” gives the basic settings of the studies. In addition, important findings are also provided.

3.1 Pedestrian Speed

The speed of pedestrians is a major issue in the design and optimization of pedestrian facilities and is an important metric for crossing efficiency and comfort. It has been studied against a number of factors for different purposes such as flashing green phase determination. Some of the variables considered are pedestrian age, gender, group size, physical disability, type of crossing, and signal phase (Hediyeh et al. 2014). The speed of pedestrians in different places at different times might be slightly different. Ishaque et al. (2008) made a review of pedestrian speeds at road crossings including not only the mean values of speed but also the 15 percentile values and sometimes for the entire range of speed distribution, which can be applied to determine parameters in simulation models. Based on related studies, some consensuses are summarized.

1. The walking speed for single pedestrians is higher than those who walked in groups, and the increase of group size can decrease the average speed (Hussein et al. 2015; Zaki and Sayed 2017).
2. Males tend to be slightly faster than females (Hussein et al. 2015; Avineri et al. 2012).
3. Violators tend to have higher walking speeds compared with non-violators (Russo et al. 2018; Zhuang et al. 2018).
4. Pedestrians who are distracted by other activities tend to have slower walking speeds (Hatfield and Murphy 2007).

3.2 Pedestrian Violations

Violations mean crossing a street illegally. This type of behavior usually happens at signalized intersections. Typically, there are three phases for pedestrians: green phase, red phase, and flashing green phase. Although slightly different regulations exist among countries, a general rule is that pedestrians are not allowed to start crossing during the green flashing phase and those who have already been on the crosswalks need to finish before the onset of the red phase. They are not allowed to cross during the red phase. Based on observations (Zhuang et al. 2018; Ren et al. 2011), in most cases, the required speed for jaywalking pedestrians to cross the street before the red phase is higher than their actual speed. Jaywalking brings potential risks to pedestrians and is closely related to risks and crashes. The relative risk ratio analysis of King et al. (2009) showed that crossing against the lights and crossing close to the lights both exhibited a crash risk per crossing event approximately eight times higher than that of legal crossing at signalized intersections.

The pedestrian violation phenomenon is quite common in urban intersections. The field study of Zhuang et al. (2018) found that 85.2 % of the pedestrians made the decision to cross during the green flashing phase, and 79 % of them did not finish crossing before the onset of the red phase. Ren et al. (2011) observed that 37.2 % of pedestrians crossed during the red phase, and the percentage is close to that of Hussein et al. (2015) and Lee and Lam (2008). The largest proportion of them violated traffic rules to save time and for convenience.

Many factors affect the crossing behavior of pedestrians. Corresponding countermeasures can be applied to improve pedestrian compliance at intersections. Statistical analysis is helpful to find latent factors. The significant factors affecting traffic signal compliance by pedestrians were systematically identified (Marisamynathan and Perumal 2014; Zhao et al. 2019). Basically, pedestrians are more likely to violate the rule when they are young men, not with distractions, in a group and have waited for a long time

(Hatfield and Murphy 2007; Ren et al. 2011; Ma et al. 2015).Many studies built models to predict the cross decision and corresponding behaviors, which are further reviewed in section 4.

Table 1: Pedestrian behavior at intersections.

Author	**Data Source**	**Description**	**Important Findings**
Hussein et al. 2015	Video	Speed and gait parameters were extracted to find the main factor in pedestrian and vehicle conflicts.	Pedestrian speed, step frequency, and step length follow the normal distribution. Pedestrian violations are the major contribution of conflicts.
Avineri et al. 2012	Video and questionnaire (203 samples)	Two specific aspects of crossing behavior: crossing speed and head pitches were analyzed.	Age and gender have the most significant effects on crossing speed, and the effect of fear of falling has a significant effect on the proportion of downward head pitches during crossing roads.
Zaki and T. Sayed 2018	Video	The study localized pedestrians in small groups using automated computer vision tracking at a moderate dense crosswalk.	There is a significant difference in the walking behavior of pedestrians belonging to the same group compared to pedestrians walking closely but in different groups or just walking alone.
Russo et al. 2018	Video (3038 samples at four signalized intersections)	Pedestrians were divided into 5 categories: no distraction, talking on mobile phones, texting, listening to headphones, or others.	Pedestrians wearing headphones tend to walk faster than undistracted pedestrians and pedestrians with other distractions exhibit slower walking speed than undistracted pedestrians. Males are more likely to violate.
Ma et al. 2015	Video and questionnaire	This study conducted a systematic analysis of a countdown pedestrian signal display (CPSD) to reveal its impacts on efficiency and safety in the total crossing process.	The compliance rate of the older age group increases significantly with the introduction of a countdown while there is no change to the younger age. CPSD increases the proportion of successful crossings of pedestrians arriving during the signal change interval and entering the crosswalk.
Zhuang et al. 2018	Field observation (486 samples)	This field study analyzed pedestrian choices after arrival, evaluated safety of the choices, and built a model to identify the factors of pedestrian choices.	Pedestrians are more likely to cross immediately after arrival when they are younger, are not engaged in secondary tasks, arriving at a position farther from approaching vehicles at the near side of the road, or arriving at a time when more pedestrians are crossing the road.
Marisamynathan and Perumal 2014	Video (775 samples)	The factors affecting compliance were identified by Pearson's correlation coefficient test, the ANOVA test, and the Student t-test.	The pedestrian age and departure signal phase have high effects on crossing speed variations. Gender and group size of pedestrians are significant factors affecting pedestrian compliance behavior.

4 MODELING TECHNIQUES

The behavior should be modeled based on observations. Further, the collected data can then be used for constructing behavior models of pedestrians, which can provide a high-level understanding of the interactions between crowds, vehicles, and infrastructure. Pedestrian behavior has been classified into three different levels: strategic level, tactical level, and operational level (Hoogendoorn and Bovy 2004). This study focuses on the third one. At the operational level, pedestrian behavior involves instantaneous decisions that affect pedestrian walking characteristics such as the choice to walk fast, or slow, or stop and wait, and when to cross a street.

This section focuses on models that can be applied to simulate the behavior of different kinds of pedestrians. Estimating when and how pedestrians will cross intersections is a challenging task, since they can move in many different directions, suddenly change motion, or be occluded by a variety of obstacles and distractions. Moreover, their decisions can also be affected by several factors. The models are built using agent attributes (e.g., position, speed), probability distribution functions, characteristics (e.g., gender, age), and external contexts (e.g., traffic light phase). The complexity of a model is chosen based on the situations, applications, and the collected data, varying from simple linear regression models to complex models, such as neural networks.

In Table 2, representative papers are reviewed to gain insights into the current research on the models of pedestrian behavior at the intersections.

4.1 Gap Acceptance Model

Pedestrians are at risk whenever they need to share the road with vehicles, especially where vehicles are not ready to yield to them. Pedestrians need to choose to cross or not based on not only their observations but also personal characteristics. A gap is defined as the time and space separating two consecutive vehicles on a major road approaching the intersection, and gap size can be described both temporally and spatially. Gap acceptance can be described as whether the pedestrian will seize the gap and cross the street. To describe the gap acceptance phenomenon and compute the likelihood of pedestrian accepting a gap at crosswalks. Researchers have developed models based on environmental and behavioral factors. Different types of intersections have different features and regulations, and pedestrians can behave differently. Thus, the following reviews literature according to signalized and unsignalized scenarios.

4.1.1 Unsignalized Intersection

The unsignalized intersection is implemented at a relatively low-volume traffic area because it is cost-efficient and easy to regulate. There is no specific traffic light to protect pedestrians with specialized time to cross the street. Zhao et al. (2019) considered six environmental factors, and a logistic regression model was established to compute the gap acceptance probability. The manner of using mobile phones is considered by Pešić et al. (2016). “Dilemma zone” is defined statistically as “the road segment where more than 10 % and less than 90 % of the drivers would choose to stop” (Shirari and Morris 2016). Dilemma zone for pedestrians at unsignalized intersections is a roadway segment where the presence of vehicles results in a stage of confusion for pedestrians while making crossing decisions, because pedestrians are often unable to correctly estimate the risk. Based on the concept of the gap acceptance model, the dilemma zone for pedestrians can be seen as a special case of gap acceptance model only considering the gap size. Pawar et al. (2016) analyzed and quantified the dilemma zone for crossing pedestrians at uncontrolled mid-block crossings. The dilemma zone was determined by using the average value of multiple methods.

4.1.2 Signalized Intersection

Most of the intersections of main roads are signalized in urban areas where the volume is higher. Although the pedestrian green phase exists to give pedestrians specific time to enter crosswalks, gap acceptance behaviors also happen at signalized crosswalks. First, many pedestrians choose to cross illegally instead of waiting to save time. Koh and Wong (2014) studied the gap acceptance behavior of violators at signalized crosswalks. Logistic regression was used to model the probability of a pedestrian accepting gaps. However, due to the data type, it cannot include personal factors like gender or age into the model. Second, although pedestrians have the right of way over vehicles, turning vehicles still compete with pedestrians. The probabilistic gap acceptance model of left-turners (left-hand traffic) considering pedestrian characteristics was built by Alhajyaseen et al. (2013) using a cumulative Weibull distribution. The developed model is intended to be incorporated into a microscopic simulation environment designed for the safety assessment of signalized intersections. In particular, Iryo-Asano et al. (2014) analyzed and modeled pedestrian crossing behavior during the pedestrian flashing green interval containing more than the pedestrians' decision of whether to cross, as well as the pedestrian speed distribution. Empirical data analysis showed that longer crosswalks lead to significantly higher pedestrian stop probabilities. The model can closely present the significant difference between the pedestrians' speeds in the first and second halves of crosswalks. To conclude, the gap acceptance behavior in various situations is widely studied and relatively simple models are applied.

4.2 Dynamic Model

As reviewed in Section 3, pedestrian behavior has highly dynamic property, and a more detailed analysis during the crossing is needed. The dynamic models focus on the change of pedestrian motion patterns such as speed and motion mode. Iryo-Asano and Alhajyaseen (2017) considered the sudden speed change events of pedestrians when entering the area of conflict with vehicles. A probabilistic discrete choice model was developed to determine acceleration and deceleration timing. The amount of speed change before and after the event was modeled using regression analysis. Pedestrian-pedestrian interaction is not considered and this model is suitable under uncongested conditions. Hashimoto et al. (2016) built a probability graph model based on the Dynamic Bayesian Network to predict the probability of crossing choice and the switching between the pedestrian behavior (standing, walking, and running) when they face left-turning vehicles at signalized crosswalks. Koehler et al. (2013) focused on stationary detection of the pedestrian's intention to enter the traffic lane at intersections. They proposed a novel MCHOG method in combination with Support Vector Machine (SVM) classification that reaches an accuracy of 99 % within the initial step at the curb. Goldhammer et al. (2013) focused on the early prediction of a pedestrian's short time trajectory in the course of gait initiation at a crosswalk. These models assume that contextual information (such as the state of traffic signal and pedestrian movement) also are available, which can be provided by V2I communication. Thus, the pedestrian behavior prediction models can be applied in real situations and are becoming an important part of ADAS and smart infrastructure systems (Ridel et al. 2018).

5 RECOMMENDATION FOR SIMULATION

Some of the reviewed papers in Section 4 are from traffic research journals and meetings, and might not directly relate to simulation. But, these studies explored the models and simulations to describe pedestrian behavior at the intersection environment interacting with vehicles and infrastructure. These studies can help to improve traffic simulations that incorporate pedestrians. Simulation can be an important application for pedestrian behavior models in order to concentrate on the impact of pedestrian choice and dynamic property as well as pedestrian-vehicle conflicts. This section obtains the major limitations of the current traffic simulations studies involving pedestrians, and recommendations for these issues are suggested in the following.

5.1 Existing Simulation Studies

Microscopic simulation has always been an important tool for problems that are difficult to do field experiments and has been steadily improving over the last decade with improvements in computational technologies (Pel et al. 2012; Xu et al. 2014). In comparison to macroscopic models, microscopic models provide a more detailed description of pedestrian behavior. The microscopic traffic simulation models involving pedestrians can apply to intersection infrastructure planning and design and can be used as helpful tools for safety and capacity assessment of road facilities, pedestrians facility assessment, and cooperative intersection systems.

Table 2: Behavior analysis at intersections.

Author	Topic	Methodology	Variables	Findings & Applications
Zhao et al. 2019	Gap acceptance model at unsignalized intersections	Logistic regression	Gap size, crossing distance, number of waiting pedestrians, waiting time, vehicle traffic volume, and position of the pedestrian	Gap size and crossing distance have the highest influence on crossing behavior. Moreover, with the increase of waiting time, the gap acceptance probability increases under the same conditions.
Pešić et al. 2016	Model for predicting unsafe behavior at unsignalized intersections	Logistic regression	Gender, age, number of accompanying pedestrians, the manner of mobile phone use, the location of the intersection	Mobile phone talking has the greatest effect on the unsafe behavior of pedestrians while listening to music has the smallest impact.
Pawar et al. 2016	Dilemma zone analysis at unsignalized intersections	The binary logit method, SVM, the probabilistic method	Spacial gap distance, the speed of coming cars	The upper and lower boundaries of the dilemma zone can be further used to develop a pedestrian assistance system at mid-block crossings for the safe movement of pedestrians.
Koh and Wong 2014	Gap acceptance model of violators at signalized intersections	Logistic regression	Personal characteristics, available gap length, gap type (with or without last passing vehicle), and stage of crossing	A greater understanding of the pedestrians' behavior at the crossings helps to alert motorists of the occurrence of potential risky pedestrian (accepting short gaps) in the pedestrian stream, hence reducing chances of conflicts or accidents.
Alhajyaseen 2013	Left-turn gap acceptance model at signalized intersections	Cumulative Weibull distribution function	Temporal lag/gap size, lag/gap type (5 types)	Drivers tend to accept shorter lags/gaps between near-side pedestrians compared to far side pedestrians. The conflicts that occur at low pedestrian demand levels are more severe compared to those at high demand levels.
Iryo-Asano et al. 2014	Pedestrian behavior model at the onset of the pedestrian flashing green (PFG)	Binomial logit model and Gamma distribution	Distance to a crosswalk, the speed at the onset of PFG, crosswalk length, pedestrian demand	The stop-go decision model and speed distribution model provide the quantitative representation of pedestrian maneuvers. The occurrence probability and severity of pedestrian-vehicle conflicts can be simulated and quantitatively evaluated.

Author	Topic	Methodology	Variables	Findings & Applications
Iryo-Asano and Alhajyaseen 2017	Speed change behavior model at signalized intersections	Discrete choice model, Linear regression	The necessary walking speed to complete crossing before the red interval ends, current speed, and the presence of turning vehicles in the conflict area	Monte Carlo simulation of the speed profile shows that the model can represent the pedestrian travel time distribution more accurately than the constant speed model. It can be utilized to estimate the pedestrian-vehicle conflict risk as part of traffic simulations for safety assessment.
Hashimoto et al. 2016	Crossing behavior model at signalized intersections	Dynamic Bayesian Network	The state of the traffic signal, pedestrian intention, motion type, and pedestrians physical state	It can recognize the pedestrian crossing decision in a few seconds from the traffic signal and pedestrian position information.
Koehler et al. 2013	Model pedestrian's intention to enter the lane	Motion Contour Image-based HOG-like descriptor in combination with SVM	Video data	It indicates that a pedestrian intends to enter the lane within 120–340 ms at an accuracy level of >80 %. The infrastructure-based prediction is aiming at an improvement of road safety by combining infrastructure information with local vehicle data.

Simulation of pedestrian behavior has been applied to multiple scenarios such as crowd movement and evacuation. These include models where people are modeled as particles or circles with different diameters and velocities (Werner and Helbing 2003; Seyfried et al. 2006; Guo et al. 2010). The movement of pedestrian crowds has also been compared with that of flowing fluids (Hughes 2003). Other models have also been developed based both on cellular automata (Blue and Adler 2001) and agent-based approaches (Kneidl et al. 2013; Hoogendoorn and Bovy 2004).

Different from crowd simulation, simulation of pedestrian behavior at intersections is a complex behavioral and engineering issue and needs to consider more relationships, for example, the interaction with turning vehicular traffic, counter-flow pedestrians, and traffic regulations. Thus, most of the pedestrian dynamic simulation tools cannot be directly used to analyze the people in the traffic environment. Pedestrian simulation usually serves as a module in traffic simulation tools. For example, among existing popular traffic simulation tools, SUMO, which is open-source, supports researchers with providing an API for different traffic models (Lopez et al. 2018) and enables the simulation of pedestrians using configurable models. The commercial software VISSIM has a pedestrian simulation module and provides two models, the Wiedemann model (pedestrians are modeled as vehicle type) and the Social Force model (Werner and Helbing 2003). Many studies used VISSIM to implement pedestrian analysis at intersections. Isaque and Noland (2009) defined pedestrians as vehicles and calibrated various parameters, and Suh et al. (2013) modeled pedestrians using the Social Force model, attempting to replicate observed pedestrian behavior at a crosswalk. Ishaque and Noland (2007) examined cost trade-offs between pedestrians and vehicles in various phasing scenarios. Overall, the Social Force model is preferred because it is more flexible, detailed, and realistic. In Table 3, representative papers are reviewed to gain insights into the current research on the traffic simulations involving pedestrians.

5.2 Limitations

Although existing traffic simulation software and frameworks provide a friendly user interface and mature vehicular models, the simulation outputs of the software appeared to be highly sensitive to the pedestrian-related parameters (Suh et al. 2013). Thus, simulations do not adequately replicate pedestrian behavior if the parameters are not set correctly. The parameter tuning process is subjective and highly empirical.

Many existing traffic simulation tools assume that all pedestrians follow the traffic rules and move following predefined routes. Thus, the pedestrian violation behavior is ignored. Also, the pedestrians have no individual characteristics and relationships with each other in these studies, while these are factors affecting pedestrian behavior. Thus, the existing simulation results can not reflect the complex and random nature of the pedestrian movement as well as corresponding effects interacting with crowds and vehicles in the real world.

Last but not the least, pedestrian-vehicle conflicts are hard to define in existing simulation studies, and simulation-based risk studies between individuals and vehicles usually introduce their own definitions regarding near-accidents or unsafe situations. Therefore, the standard needs to be unified.

Table 3: Traffic simulation study of pedestrians at intersections.

Author	Topic	Tools / Methodology	Environment
Zeng et al. 2017	A microscopic model for pedestrian dynamic simulation	Social Force model	Signalized intersection
Isaque and Noland 2009	Pedestrian and vehicle flow calibration in multimodal traffic microsimulation	VISSIM; Wiedemann model.	The simulated Marylebone Road in London
Suh et al. 2013	Modeling pedestrian crossing activities	VISSIM; Social Force model.	The simulated intersection in Atlanta
Erdmann and Krajzewicz 2015	Modeling pedestrian and bicycle traffic dynamics in SUMO	SUMO; cellular automata.	Signalized intersection

5.3 Recommendations

First, a more scientific parameter calibration method is needed in simulations. To fit the observation data, state-of-the-art studies provided a more flexible and systematic simulation and calibration process. The parameters, including measurable and non-measurable ones, are either directly estimated based on the observed dataset or indirectly derived by maximum likelihood estimation (Zeng et al. 2014) and genetic algorithms (Zeng et al. 2017). The simulation performance was verified by various real-world terms, such as instant position, instant speed, pedestrian trajectory, collision avoidance behavior with conflicting vehicles, and lane-formation phenomena. The parameter calibration process can give more credits to the simulation results to guide real-world applications.

Second, the models in Section 4 can be incorporated to better describe pedestrian behavior. Thus a modified pedestrian simulation model considering the typical pedestrian behavior at signalized intersections, e.g., gap acceptance, group evasive and individual evasive maneuver, collision avoidance with turning vehicles, and speed change should be established. Moreover, the agent-based simulation has advantages in modeling a lot of agents or active entities interacting with each other with certain inherent attributes. Thus, the agent-based approach is expected to obtain more-realistic results than the cases where the pedestrians are uniformly modeled. The existing agent-based simulation tools are comprehensively reviewed by Abar et al. (2017) and they have achieved satisfactory results in pedestrian behavior simulation (Ronald et al. 2007). However, few studies applied these methods into traffic environments where vehicles and traffic rules coexist. Other participants at intersections can also be modeled as autonomous agents with their own knowledge and goals.

Third, most pedestrian safety analyses were estimated using data mining techniques on observed data, accident reports, and collision datasets. Thus, simulation should play a more important role in assessing the risks that pedestrians are facing as an alternative tool, because simulation can overcome the difficulty and high cost of collecting accident data. For example, Wu et al. (2018) defined a pedestrian-to-vehicle conflict at signalized intersections with the assistance of a software application known as "Surrogate Safety Assessment Model (SSAM)", but found that the VISSIM model might underestimate the number of pedestrian-vehicle conflicts at specific intersections. It is recommended that reasonable estimates for pedestrian-vehicle conflicts should be provided in simulation.

To summarize, there is still no ideal method available to integrate the modeling of pedestrian and vehicular traffic. The modeling and simulation of the interaction among vehicles and pedestrians at intersections is an open challenge for both research and practical computational solutions supporting urban/traffic decision-makers and managers.

6 CONCLUSIONS

This paper has provided a literature review on the studies of pedestrian behavior at intersections. Behavior analysis shows the highly complex nature of pedestrian behavior and the role of multiple influencing factors. Based on that, this review has highlighted the wide variations of models of pedestrian behavior. The models mostly consider pedestrians for active decision-makers compared with models in which pedestrians are treated as passive receivers of a series of heuristics. It can increase the accuracy and reliability and be applied to design on-board driver alert systems, as well as ADAS of vehicles that operate in close proximity to pedestrians. As for recommendations, the models can increase the accuracy and reliability of traffic simulations that incorporate pedestrians, as it can accurately simulate the pedestrians' behavior at a microscopic level.

This paper concludes with some guidelines for further research in these areas that can lead to a better understanding of intersection management. First, the reviewed area lacks a comprehensive database regarding pedestrians and vehicles, which can be an obstacle to compare related studies. A precondition for comparison is that a universally consistent definition of the pedestrian risk should be defined. Second, except for signalization, the characteristics of intersections such as the layout, the number of lanes, safe islands and signs, and roundabouts can affect pedestrian behavior. There are various types of intersections in the real environment, while the influence of different layouts and structure is less studied. Thus, future studies can quantify and compare the difference in pedestrian behavior at typical intersections. In addition, future traffic will be highly automated (Evanson 2017). It should be considered how the automated vehicles will interact with pedestrians and which information is needed to enhance safety. Proper usage of infrastructure cooperatively with well-equipped vehicles can boost cooperative intersection development. Pedestrian behavior modeling and simulation studies can give intuitions before conducting field experiments.

We believe the next step for the evolution of the state-of-the-art on the traffic simulation of pedestrians' behavior will benefit to the development of ADAS as well as intelligent intersection management. Intersections will provide better protection for pedestrians and improve efficiency.

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REFERENCES

Abar, S., G. K. Theodoropoulos, P. Lemarinier, and G. M. O'Hare. 2017. "Agent Based Modelling and Simulation Tools: A Review of the State-of-art Software". *Computer Science Review* 24:13–33.

Alhajyaseen, W. K. M., M. Asano, and H. Nakamura. 2013. "Left-Turn Gap Acceptance Models Considering Pedestrian Movement Characteristics". *Accident Analysis and Prevention* 50:175–85.

Avineri, E., D. Shinar, and Y. O. Susilo. 2012. "Pedestrians' Behaviour in Cross Walks: The Effects of Fear of Falling and Age". *Accident Analysis and Prevention* 44(1):30–34.

Blue, V. J., and J. L. Adler. 2001. "Cellular Automata Microsimulation for Modeling Bi-directional Pedestrian Walkways". *Transportation Research Part B: Methodological* 35(3):293–312.
Erdmann, J., and D. Krajzewicz. 2015. "Modelling Pedestrian Dynamics in SUMO". *SUMO 2015 – Intermodal Simulation for Intermodal Transport* 28:103–118.
Evanson, A. 2017. "Connected Autonomous Vehicle (CAV) Simulation Using PTV Vissim". In *Proceedings of the 2017 Winter Simulation Conference*, edited by W. K. V. Chan, A. D'Ambrogio, G. Zacharewicz, N. Mustafee, G. Wainer, and E. Page, 4420–4420. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.
Geronimo, D., A. M. Lopez, A. D. Sappa, and T. Graf. 2009. "Survey of Pedestrian Detection for Advanced Driver Assistance Systems". *IEEE transactions on Pattern Analysis and Machine Intelligence* 32(7):1239–1258.
Goldhammer, M., M. Gerhard, S. Zernetsch, K. Doll, and U. Brunsmann. 2013. "Early Prediction of a Pedestrian's Trajectory at Intersections". In *16th International IEEE Conference on Intelligent Transportation Systems*, October 6th–9th, The Hague, Netherland, 237–242.
Guo, R. Y., S. C. Wong, H. J. Huang, P. Zhang, and W. H. Lam. 2010. "A Microscopic Pedestrian-simulation Model and Its Application to Intersecting Flows". *Physica A: Statistical Mechanics and its Applications*, 389(3):515–526.
Hashimoto, Y., Y. Gu, L. T. Hsu, M. Iryo-Asano, and S. Kamijo. 2016. "A Probabilistic Model of Pedestrian Crossing Behavior at Signalized Intersections for Connected Vehicles". *Transportation Research Part C: Emerging Technologies* 71:164–181.
Hatfield, J., and S. Murphy. 2007. "The Effects of Mobile Phone Use on Pedestrian Crossing Behaviour at Signalised and Unsignalised Intersections". *Accident Analysis and Prevention* 39(1):197–205.
Hediyeh, H., T. Sayed, M. H. Zaki, and G. Mori. 2014. "Pedestrian Gait Analysis Using Automated Computer Vision Techniques". *Transportmetrica A: Transport Science* 10(3):214–232.
Hoogendoorn, S. P., and P. H. L. Bovy. 2004. "Pedestrian Route-choice and Activity Scheduling Theory and Models". *Transportation Research Part B: Methodological* 38(2):169–190.
Hughes, R. L. 2003. "The Flow of Human Crowds". *Annual Review of Fluid Mechanics* 35(1):169–182.
Hussein, M., T. Sayed, P. Reyad, and L. Kim. 2015. "Automated Pedestrian Safety Analysis at a Signalized Intersection in New York City: Automated Data Extraction for Safety Diagnosis and Behavioral Study". *Transportation Research Record* 2519:17–27.
Iryo-Asano, M., W. K. Alhajyaseen, and H. Nakamura. 2014. "Analysis and Modeling of Pedestrian Crossing Behavior During the Pedestrian Flashing Green Interval". *IEEE Transactions on Intelligent Transportation Systems* 16(2): 958–969.
Iryo-Asano, M., and W. K. M. Alhajyaseen. 2017. "Modeling Pedestrian Crossing Speed Profiles Considering Speed Change Behavior For the Safety Assessment of Signalized Intersections". *Accident Analysis and Prevention* 108:332–342.
Ishaque, M. M., and R. B. Noland. 2007. "Trade-offs Between Vehicular and Pedestrian Traffic Using Micro-simulation Methods". *Transport Policy* 14(2):124–138.
Ishaque, M. M., and R. B. Noland. 2008. "Behavioural Issues in Pedestrian Speed Choice and Street Crossing Behaviour: A Review". *Transport Reviews* 28(1): 61‑85.
Ishaque, M. M., and R. B. Noland. 2009. "Pedestrian and Vehicle Flow Calibration in Multimodal Traffic Microsimulation". *Journal of Transportation Engineering* 135(6): 338‑48.
King, M. J., D. Soole, and A. Ghafourian. 2009. "Illegal Pedestrian Crossing at Signalised Intersections: Incidence and Relative Risk". *Accident Analysis and Prevention* 41(3): 485‑90.
Koehler, S., M. Goldhammer, S. Bauer, S. Zecha, K. Doll, U. Brunsmann, and K. Dietmayer. 2013. "Stationary Detection of the Pedestrian's Intention at Intersections". *IEEE Intelligent Transportation Systems Magazine* 5(4): 87‑99.
Koh, P. P., and Y. D. Wong. 2014. "Gap Acceptance of Violators at Signalised Pedestrian Crossings". *Accident Analysis and Prevention* 62:178‑85.
Kneidl, A., D. Hartmann, and A. Borrmann. 2013. "A Hybrid Multi-scale Approach for Simulation of Pedestrian Dynamics". *Transportation research part C: emerging technologies* 37: 223–237.
Leden, L. 2002. "Pedestrian Risk Decrease with Pedestrian Flow. A Case Study Based on Data from Signalized Intersections in Hamilton, Ontario". *Accident Analysis and Prevention* 34(4): 457–64.
Lee, C., and M. Abdel-Aty. 2005. "Comprehensive Analysis of Vehicle-Pedestrian Crashes at Intersections in Florida." *Accident Analysis and Prevention* 37 (4): 775‑86.
Lee, J. Y., and W. H. Lam. 2008. "Simulating Pedestrian Movements at Signalized Crosswalks in Hong Kong". *Transportation Research Part A: Policy and Practice* 42(10):1314–1325.
Lopez, P. A., M. Behrisch, L. Bieker-Walz, J. Erdmann, Flötteröd, Y. P., Hilbrich, R, and Wießner, E. 2018. "Microscopic Traffic Simulation Using Sumo". In 21st *International IEEE Conference on Intelligent Transportation Systems*, November 4th–7th, Maui, USA, 2575–2582.
Ma, W., D. Liao, and Y. Bai. 2015. "Empirical Analysis of Countdown Signals on Pedestrian Behaviour." *Proceedings of the Institution of Civil Engineers: Transport* 168(1): 15–22.
Marisamynathan, and Perumal, V. (2014). "Study on Pedestrian Crossing Behavior at Signalized Intersections". In *Proceedings of the 14th COTA International Conference of Transportation Professionals*, July 4th–7th, Changsha, China, 2641–2652.
Pawar, D. S., V. Kumar, N. Singh, and G. R. Patil. 2016. "Analysis of Dilemma Zone for Pedestrians at High-Speed Uncontrolled Midblock Crossing". *Transportation Research Part C: Emerging Technologies* 70: 42–52.

Pešić, D., B. Antić, D. Glavić, and M. Milenković. 2016. "The Effects of Mobile Phone Use on Pedestrian Crossing Behaviour at Unsignalized Intersections – Models for Predicting Unsafe Pedestrians Behaviour". *Safety Science* 82: 1–8.
Ren, G., Z. Zhou, W. Wang, Y. Zhang, and W. Wang. 2011. "Crossing Behaviors of Pedestrians at Signalized Intersections: Observational Study and Survey in China". *Transportation Research Record* 2264: 65–73.
Ridel, D., E. Rehder, M. Lauer, C. Stiller, and D. Wolf. 2018. "A Literature Review on the Prediction of Pedestrian Behavior in Urban Scenarios". In *21st International IEEE Conference on Intelligent Transportation Systems*, November 4th–7th, Maui, USA, 3105–3112.
Ronald, N., L. Sterling, and M. Kirley. 2007. "An Agent-based Approach to Modelling Pedestrian Behaviour". *International Journal of Simulation* 8(1): 25–38.
Russo, B. J., E. James, C. Y. Aguilar, and E. J. Smaglik. 2018. "Pedestrian Behavior at Signalized Intersection Crosswalks: Observational Study of Factors Associated with Distracted Walking, Pedestrian Violations, and Walking Speed". *Transportation Research Record* 2672 (35): 1–12.
Seyfried, A., B. Steffen, and T. Lippert. 2006. "Basics of Modelling the Pedestrian Flow". *Physica A: Statistical Mechanics and its Applications* 368(1): 232–238.
Shirazi, M. S., and B. T. Morris. 2017. "Looking at Intersections: A Survey of Intersection Monitoring, Behavior and Safety Analysis of Recent Studies". *IEEE Transactions on Intelligent Transportation Systems* 18(1): 4-24.
Suh, W., D. Henclewood, A. Greenwood, A. Guin, R. Guensler, M. P. Hunter, and R. Fujimoto. 2013. "Modeling Pedestrian Crossing Activities in an Urban Environment Using Microscopic Traffic Simulation". *Simulation* 89 (2): 213-24.
Tiwari, G., S. Bangdiwala, A. Saraswat, and S. Gaurav. 2007. "Survival Analysis: Pedestrian Risk Exposure at Signalized Intersections". *Transportation Research Part F: Traffic Psychology and Behaviour* 10(2): 77-89.
Wang, X., H. Yu, C. Nie, Y. Zhou, H. Wang, and X. Shi. 2019. "Road Traffic Injuries in China from 2007 to 2016: The Epidemiological Characteristics, Trends and Influencing factors". *PeerJ* 7: e7423.
Werner, T., and D. Helbing. 2003. "The Social Force Pedestrian Model Applied to Real Life Scenarios. In Pedestrian and Evacuation Dynamics". In *Proceedings of the 2nd International Conference on Pedestrian and Evacuation Dynamics,* August 20th–22nd, Greewich, UK, 17–26.
World Health Organization. 2018. *Global Status Report on Road Safety 2018*. World Health Organization. http://www9.who.int/violence_injury_prevention/road_safety_status/2018/en/, accessed December 2018.
Wu, J., E. Radwan, and H. Abou-Senna. 2018. "Determination if VISSIM and SSAM Could Estimate Pedestrian-Vehicle Conflicts at Signalized Intersections". *Journal of Transportation Safety and Security* 10(6): 572–85.
Xu, M. L., H. Jiang, X. G. Jin, and Z. Deng. 2014. "Crowd Simulation and its Applications: Recent Advances". *Journal of Computer Science and Technology* 29(5): 799–811.
Zaki, M. H., and T. Sayed. 2018. "Automated Analysis of Pedestrian Group Behavior in Urban Settings". *IEEE Transactions on Intelligent Transportation Systems* 19 (6):1880-89.
Zeng, W., P. Chen, H. Nakamura, and M. Iryo-Asano. 2014. "Application of Social Force Model to Pedestrian Behavior Analysis at Signalized Crosswalk". *Transportation research part C: emerging technologies* 40:143–159.
Zeng, W., P. Chen, G. Yu, and Y. Wang. 2017. "Specification and Calibration of a Microscopic Model for Pedestrian Dynamic Simulation at Signalized Intersections: A Hybrid Approach". *Transportation Research Part C: Emerging Technologies* 80:37–70.
Zhao, J., J. O. Malenje, Y. Tang, and Y. Han. 2019. "Gap Acceptance Probability Model for Pedestrians at Unsignalized Mid-Block Crosswalks Based on Logistic Regression". *Accident Analysis and Prevention* 129 (January):76–83.
Zhuang, X., C. Wu, and S. Ma. 2018. "Cross or Wait? Pedestrian Decision Making during Clearance Phase at Signalized Intersections". *Accident Analysis and Prevention* 111:115–24.

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