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Dynamic model for pedestrian crossing in congested traffic based on probabilistic navigation function

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ABSTRACT

More than 1.2 million people die in road crashes each year, and more than 20 million are severely injured, making it the 9th leading cause of death in the world (2.2% of all deaths globally). Pedestrian deaths comprise more than 35% of road accident deaths, mostly as a result of pedestrian-vehicle crashes. This paper proposes a new model for formulating the dynamics of the interaction between drivers and pedestrians at congested conflict spots where drivers and/or pedestrians do not closely follow the traffic laws and regulations. In this type of spots, characterized by heavy traffic, pedestrians and vehicles interact in close proximity, often requiring sharp and aggressive maneuvers to avoid crashes. The model is based on the Probabilistic Navigation Function (PNF), originally developed for robotics motion planning, that constructs a trajectory according to the probabilistic collision risks. According to this model, pedestrians construct a virtual risk map that assigns the entire crossing area with probabilities for a collision with vehicles, and then select their actions based on their perceived probability for collision. Many accidents can be interpreted in terms of the proposed model, either as a result of incorrect perception of risks, or, despite proper estimation of risks, by a wrong choice of collision maneuvers. The development of the model follows a theoretical and experimental investigation of pedestrian/vehicle interactions at crosswalks. The model is implemented in an agent-based simulation system for pedestrian/driver interaction, and is validated using video clips taken at several congested road spots. It can be used for analyzing the effect of changes in location architecture and traffic regulations for each spot. The model can also serve as a standard tool in simulations for assessing accident risks in urban environments. Finally, it can be utilized in control systems of autonomous vehicles and in drivers' on-board alert systems.

1. Introduction

According to the United Nations World Health Organization statistics from 2016, traffic accidents caused more than 1.24 million deaths and 20 million severe injuries in 2010 alone, with low and middle income countries leading the death rate at 20.1 per 100,000 citizens. According to this report, 90% of the fatalities on roads occur in these countries, although the number of vehicles is much lower than in high income countries. While in some countries the traffic laws and regulations are the dominant factors in the interaction between vehicles and pedestrians, many drivers and pedestrians in other countries consider the terms "right of way", "pedestrian crossing", "signaling" etc. as little more than recommendations. Traffic accidents are the major cause of death and permanent disabilities for people under the age of 35, with financial damage estimated at more than US$ 500 billion. Road crashes

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are the leading cause of death among young people aged 15–29, and the second leading cause of death worldwide among young people aged 5–14. More than 50% of the deaths occurred among vulnerable road users, with pedestrians comprising 35%, and bicycle and motorcycle users comprising the remaining 15%. Road traffic injuries are predicted to become the fifth leading cause of death by 2030.

The major reason for the high proportion of severe pedestrian casualties is the clear handicap of the pedestrian in a vehicle-pedestrian interaction in terms of speed, weight and protection (Moudon et al., 2011). There are conflicting reports regarding the circumstances that lead to fatal vehicle-pedestrian accidents. Rothman et al. (2012) found, based on 9,575 police reports in Toronto, that although more collisions between pedestrians and vehicles occur at signalized intersections, the severity of the accidents increases by more than 250% at unsignalized crosswalks. Pfortmueller et al. (2014) also found a higher rate of accidents at marked crosswalks, but with significantly higher severity of accidents at unmarked crosswalks. They explain the greater severity of accidents by the higher collision speeds at unmarked crosswalks, as well as by the greater involvement of larger vehicles in accidents at unmarked crosswalks. These results agree with Tefft (2013) who found that the risk for a fatal injury during a collision at a speed of 50 km/h is eight times higher than at 30 km/h. On the other hand, Jones and Tomcheck (2000) showed a significant reduction (more than 60%) in pedestrian accidents after the removal of marked crosswalks from intersections around the Los Angeles area. Although this research focused on the quantitative examination of the accidents, and did not investigate the cause for this reduction, the "exposure rate" of the pedestrian was mentioned as a possible reason.

1.1. Behavior models of crossing pedestrians

The above-mentioned studies, as well as numerous others, led researchers to investigate the behavior of pedestrians and drivers at marked and unmarked crosswalks, as well as other road sharing spots such as intersections with simultaneous green lights for a vehicular right turn and a pedestrian crossing (left turn in some countries). The heterogeneity between moving vehicles and pedestrians in terms of speeds, sizes and maneuverability is large, involving diverse static and dynamic characteristics, and therefore requires deeper understanding of driver and pedestrian behavior. Many models are based on the microscopic behavior of individual pedestrians. For example, Helbing et al. (2000) describe pedestrians as particles subjected to social forces that determine their walking patterns and their interaction with other pedestrians and with obstacles. Hoogendoorn and Bovy (2002) consider pedestrians as autonomous controllers that optimize a cost function while moving towards their target destination. Blue and Adler (2001) use Cellular Automata (CA) microsimulation to model bi-directional pedestrian motion. They show that using a simple set of rules can effectively capture the behavior of pedestrians at the micro level.

Duives et al. (2013) assess pedestrian behavior models by considering eight distinct motion-based cases and six phenomena of crowd movement. The motion-based cases are divided into uni-directional and multi-directional groups. The uni-directional cases consist of straight flow, rounding a corner, and entering and exiting. The multi-directional cases consist of uni- and bi-directional flows, random flows and two sub-cases of crossing flows (two and four crossing directions). The crowd movement phenomena consist of lane formation, stop/go waves, turbulences, herding, zipper effect and faster-is-slower effect. Bellomo et al. (2012), Helbing and Johansson (2011) and Papadimitriou et al. (2009) show that any pedestrian behavior model must fit the specific application case. In that sense, pedestrians crossing a road represent a special case of crowd movement, where although all agents have a common strategic goal (crossing the road as fast as possible), each pedestrian may have an individual target location, varying physical and mental capabilities, and different level of urgency. Hashimoto et al. (2016) developed a probabilistic model of pedestrian behavior when crossing at signalized crosswalks. The authors focused on the scenario of left-turning vehicles at signalized intersections, where the vehicles and pedestrians share the road simultaneously (right-turning in countries where vehicles drive on the right side of the road). The model uses a particle filter for estimating the pedestrian state, which includes the pedestrian position, crossing decision and motion type. The pedestrian's behavior is classified to three modes (standing, walking and running) and the probability for switching between the modes is estimated based on the distance to the edge of the crosswalk. Zhang and Duan (2007) presented a pedestrian street-crossing model using CA. The model consists of three sub-models: vehicles, pedestrians and interactions. In this model, the crosswalk area is covered by a pedestrian grid (0.5 m × 0.5 m), and by a vehicle grid (4.5 m × 3 m). At each time period, a cell can be occupied by a pedestrian, a vehicle or both. Pedestrians and drivers follow a set of predefined simplistic rules with a probabilistic distribution regarding their trajectories. The model controls the interactions between the vehicles and pedestrians, considering a variety of parameters for vehicle and pedestrian behaviors and characteristics. Simulation results with a variety of vehicle and pedestrian parameters show that pedestrian volume has the most significant effect on the capacity of crosswalks. The results also provide data for determining the optimal length of the green light for pedestrians at signalized crosswalks. Wang et al. (2011) presented a pedestrian model for mid-block crosswalks and intersections. They use a parametric duration model for investigating the relationship between pedestrians' behavior and the waiting time at crosswalks. They measured the waiting time of pedestrians at different signalized crosswalks and intersections, and used the Weibull distribution function to describe the reliability of pedestrian behavior. The results prove that the probability for violation of safe crossing is time dependent and increases with waiting time (50% of pedestrians are not willing to wait more than 40seconds). They also found that personal characteristics (e.g. pedestrian's age and physical handicaps) and traffic conditions (e.g. pedestrian and traffic flow rate) have significant influence on pedestrian violation of safe crossing.

Obviously, road behavior of both vehicles Yin et al. (2004), and pedestrians Pawar et al. (2016) is governed by risk reduction. Pedestrians are at risk whenever they need to share the road with vehicles, particularly where vehicles are not used to yielding to pedestrians. Pedestrians are often unable to correctly estimate the risk (e.g. misjudgment in estimating the gaps between vehicles) resulting in "Dilemma Zones" where the pedestrians are in a state of confusion and uncertainty while making significant decisions.