A Hybrid Control Framework for Autonomous Vehicles at Uncontrolled Intersections

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***Abstract*— As autonomous vehicles (AVs) inch closer to reality, a central requirement for acceptance will be earning the trust of humans in everyday driving situations. In particular, the interaction between AVs and pedestrians is of high importance, as every human is a pedestrian at some point of the day. This paper considers the interaction of a pedestrian and an autonomous vehicle at a mid-block, uncontrolled intersection where there is ambiguity over when the pedestrian should cross and when and how the vehicle should yield. By modeling pedestrian behavior through the concept of gap acceptance, the authors show that a hybrid controller with just four distinct modes allows an autonomous vehicle to successfully interact with a pedestrian across a continuous spectrum of possible crosswalk-entry behaviors. The controller is validated in simulation through comparison with a previously published control policy obtained through solution of a POMDP, and experimental results are provided on a Hyundai Genesis vehicle for a virtual pedestrian.**

I. Introduction

A. Motivation

While autonomous vehicles have the potential to save thousands of lives every year and create tremendous societal benefits [1], widespread adoption is unlikely until AVs gain the broad trust of society. Given that every human is a pedestrian at some point during the day, one of the central ways that autonomous vehicles will be evaluated is through their interactions with pedestrians. In fact, recent events with industry leader Waymo highlight that AV-pedestrian interaction has still not been perfected[2]. In general, interactions with pedestrians are complex, even for experienced human drivers. Issues such as lack of visibility, improper communication, poorly marked roads, and distraction on both the driver or pedestrian side can lead to accidents and fatalities. From 2015-2016, pedestrian fatalaties increased by 9% to 5987, representing the highest number since 1990, and also representing 16% of all automotive fatalities [3]. As autonomous vehicles inch closer to widespread adoption, they must have a clear control strategy for pedestrian interaction that can handle a wide variety of pedestrian behaviors while maintaining a reasonable flow of traffic.

B. Prior Art

The need to further understand pedestrian behavior for autonomous driving has created a growing body of interdisciplinary research. One branch of research has focused around modeling pedestrian behavior given various sensor inputs. Keller et al [4] presented a study on pedestrian path prediction and action classification (e.g. crossing vs. waiting) using Gaussian process dynamical models and trajectory matching from optical data. Several other techniques for pedestrian trajectory prediction have been proposed, including LQR [5], set-based reachability analysis [6], and Markov processes [7]

Another branch of literature is focused on developing predictive models for pedestrian crossing. While typically studied for purposes of road design, this body of literature holds promising insights for AV designers. For example, Schroeder and Rouphail [8] explored factors associated with driver yielding behavior at unsignalized pedestrian crossings. Using logistic regression, the authors found that drivers are more likely to yield to assertive pedestrians who walk briskly in their approach to a crosswalk. Kadali and Perumal [9] studied the "gap acceptance" behavior of pedestrians at mid-block crosswalks through a video graphic survey, and found that the gap accepted for crossing was explained by factors such as crossing direction, vehicle speed, and pedestrian age. Yannis et al. [10] and [11] also found that gap acceptance was influenced by the size of the oncoming vehicle and the presence of other pedestrians. Lee and Aty [12] studied interactions in the form of crashes, and found crashes were linked with higher daily traffic.

Finally, a small but rapidly growing body of literature specifically studies the interaction between pedestrians and autonomous vehicles at crosswalks. An excellent review of these studies was conducted by [13]. As an example, Rothenbucher et al. [14] studied the interaction between pedestrians and driverless vehicles by constructing a car seat costume to disguise a driver. The authors noted that pedestrians overall managed interactions at crosswalks effectively, but later mentioned increased uncertainty about the autonomous vehicles behavior. To improve the issue of trust, several researchers have developed external interfaces to more clearly broadcast the intent of the autonomous vehicle [15], [16].

Several real-world studies of AV-pedestrian interaction note that once a local population learned a vehicle was programmed to be perfectly safe, pedestrians would regularly take advantage of the AV and walk in front of it. [**?**]. This illustrates an issue with automated driving in that an overly conservative crossing algorithm will often be taken advantage of or cause confusion among pedestrians. Camara et al [17] attempted to model the natural negotation for priority between a pedestrian and an AV at an intersection using the framework of "sequential chicken" adopted from game theory. Chen et al. [18] notes the need for a tradeoff between passive and aggressive driving behavior, and devel-

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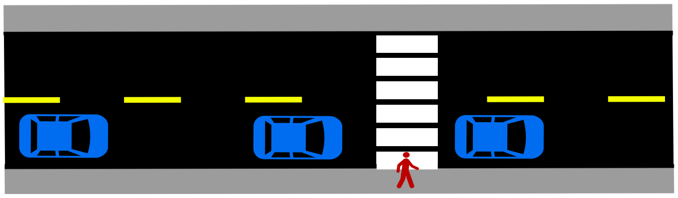

Fig. 1. Schematic of pedestrian approaching a stream of traffic at a mid-block intersection.

oped a stochastic model of pedestrian behavior to evaluate proposed AV control policies. Control polices for pedestrian interaction are also developed by [19], who proposes a Mixed-observable Markov Decision Process (MOMDP) to incorporate the intention uncertainty of a pedestrian. A POMDP formulation is also proposed by Thornton [20], who proposes navigation of the pedestrian uncertainty through value-sensitive design.

C. Statement of Contributions

Significant research has been conducted to understand the likelihood of pedestrian crossing given certain traffic conditions and pedestrian demographics [8] -[12], and a small but growing body of literature develops control strategies for pedestrian avoidance [19]-[20]. However, what is missing is a contribution that explicitly tests whether a proposed control strategy is robust to the variety of pedestrian behaviors that have been observed from experimental studies on real roads. What is also missing is analysis of how this controller should behave across multiple traffic scenarios - for example, the navigation problem is different for the pedestrian crossing on the opposing side of traffic, and also depends on which particular lane the vehicle is in.

This paper aims to address this gap by developing a hybrid control architecture that accounts for several distinct pedestrian modes of behavior at an unsignalized crosswalk. An unsignalized crosswalk is chosen as it is the trickiest crosswalk for a pedestrian and vehicle to navigate, as there is no explicit declaration of whose turn it is cross. Simulations show that the state machine controller is able to handle a continuous spectrum of pedestrian *gap acceptance* behavior, tolerating a range of highly conservative to highly aggressive pedestrians. Moreover, this is possible with just four distinct states. Simulations are also used to compare the closed-loop controller with the controller developed by [20]. Finally, experimental results are shown on a real vehicle to demonstrate the feasibility of the proposed state machine controller.

II. Problem Overview

A. Unsignalized Intersections

In general, pedestrian crosswalks may be controlled or uncontrolled. In the case of the former, control devices such as stop signs or walk signals guide the interaction of vehicles and pedestrians explicitly. Fig. 1 shows the latter example, in which a pedestrian must select a gap in traffic flow and cross.

In general, right-of-way for uncontrolled intersections is complex. For example, nine states and the District of Columbia require motorists to stop when approaching a pedestrian in an uncontrolled crosswalk. Six states require a motorist to stop when a pedestrian is upon the same half of the roadway or within one lane of the lane that the motorist is traveling upon. Another nineteen states require a motorist to yield when a pedestrian is upon any portion of the roadway, and another 20 states mandate that motorists yield when a pedestrian is upon the same half of the roadway or approaching closely from the opposite side of the roadway [**?**].

B. Pedestrian Gap Acceptance

One of the major factors that determines pedestrian crossing behavior at uncontrolled intersections is *gap acceptance*, defined in this paper as:

$$\text{gap} = \frac{\text{distance to crosswalk}}{\text{vehicle speed}} \tag{1}$$

Similar to time to collision (TTC), the safety gap is a measure of how much time there is before the vehicle would enter the crosswalk if it kept it's current speed constant. When faced with a stream of traffic at a crosswalk, a pedestrian inherently decides how much of a gap to accept before crossing. The average gap acceptance is reported in the literature to be between 3-7 seconds, meaning pedestrians usually do not cross if the vehicle would enter the crosswalk in under three seconds [21], and are very likely to cross when they have more than seven seconds [22].

C. Problem Formalization and System Requirements

A diagram of the relevant state variables is shown below in Fig. 2. We assume that knowledge of distance d to a fixed stopping point 3-5 meters ahead of the crosswalk can be estimated by a perception system, and that the velocity of the vehicle $\dot{d}$ is known as well. Furthermore, we also assume the perception system is able to determine the position of the pedestrian x_p within the crosswalk, and is able to determine a velocity estimate $\dot{x_p}$ for the pedestrian as well.

The relevant control problem is therefore to determine an appropriate longitudinal acceleration command for the vehicle, $u = \ddot{d}$, as a closed-loop function of the vehicle and pedestrian states:

$$\ddot{d} = f(d, \dot{d}, x_p, \dot{x_p}) \tag{2}$$

In general, this control problem is difficult as there are multiple stakeholders and therefore multiple competing objectives that must be considered. For example, relevant stakeholders for this problem are the autonomous vehicle and its passengers, the pedestrian(s), and the other vehicles in the traffic stream.

As a result, an algorithm that simply yields every time a pedestrian is near the crosswalk is likely to be too conservative, as there is a likelihood the pedestrian is waiting for a larger gap in the traffic stream to cross or is walking through the sidewalk without intending to cross in the first place.

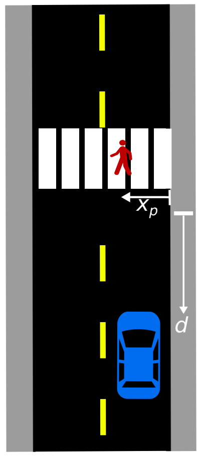

Fig. 2. Description of relevant problem variables.

To formalize the system requirements for this multi-stake holder problem, we propose the following *design constraints*, extended from the engineering specifications proposed by Thornton [20].

Engineering Specification	**Design Constraint**
1. Safety and Legality	a. Avoid collisions for all possible accepted gaps b. Ability to follow stop/yield laws for all 50 U.S. states
2. Efficiency	a. Average speed: Minimize deviation from speed of traffic b. Wait for pedestrian crossing event to materialize before yielding.
3. Smoothness	a. Low accel: Nominal brake / accel limits of 2 m/s/s b. Stop within 3-5 meters of crosswalk

III. Proposed Control Architecture

The proposed control architecture is shown below in Fig. 3, and the algorithm for operation is shown in Algorithm 1. At heart, the control algorithm uses a feedback-feedforward methodology to compute desired acceleration commands $\ddot{d}$, but computes these commands differently depending on which of four discrete states the controller is in. The next sections will describe the four states.

A. Nominal Driving

In the nominal state, the vehicle attempts to drive through the crosswalk at the speed limit $v_{\text{speedlimit}}$. A simple proportional speed control is applied to keep the vehicle at the speed limit, achieving design constraint 2.a.:

$$\ddot{d} = k_s(\dot{d} - v_{\text{speedlimit}}) \tag{3}$$

Algorithm 1 Calculate $\ddot{d} = f(d, \dot{d}, x_p, \dot{x}_p)$

$state \leftarrow DRIVING$
while true do
  if $state = DRIVING$ **then**
    $\ddot{d} \leftarrow k_s(\dot{d} - v_{\text{speedlimit}})$
    if $d > 0$ **and** $\text{inCrosswalk}(x_p)$ **then**
      if $\text{timeAdvantage}(x_p, \dot{x}_p, d, \dot{d}) > t_{max}$ **then**
        $state \leftarrow DRIVING$
      else if $d > \frac{\dot{d}^2}{2a_{\text{cmfrt}}}$ **then**
        $state \leftarrow YIELDING$
      else if $d < \frac{\dot{d}^2}{2a_{\text{cmfrt}}}$ **and** $d > \frac{\dot{d}^2}{2a_{\text{max}}}$ **then**
        $state \leftarrow HARD\ BRAKING$
      else
        $state \leftarrow SPEED\ UP$
      end if
    end if
  end if

  if $state = YIELDING$ **then**
    if $d > \frac{\dot{d}^2}{2a_{\text{cmfrt}}} + t_{delay}\dot{d}$ **then**
      $\ddot{d}_{des} = 0$
      $\dot{d}_{des} = v_{\text{speedlimit}}$
    else
      $\ddot{d}_{des} = -a_{\text{cmf}}$
      $\dot{d}_{des} = \text{getDesiredSpeed}(d, \dot{d})$
    end if
    $\ddot{d} = \ddot{d}_{des} + k_s(\dot{d} - \dot{d}_{des})$
    if not $\text{inCrosswalk}(x_p)$ **then**
      $state \leftarrow DRIVING$
    end if
  end if

  if $state = HARD\ BRAKING$ **then**
    $\dot{d}_{des} = \text{getDesiredSpeed}(d, \dot{d})$
    $\ddot{d} = -\frac{\dot{d}^2}{2d} + k_s(\dot{d} - \dot{d}_{des})$
    if not $\text{inCrosswalk}(x_p)$ **then**
      $state \leftarrow DRIVING$
    end if
  end if

  if $state = SPEED\ UP$ **then**
    $\ddot{d} = a_{\text{cmf}}$
    if not $\text{inCrosswalk}(x_p)$ **then**
      $state \leftarrow DRIVING$
    end if
  end if
end while

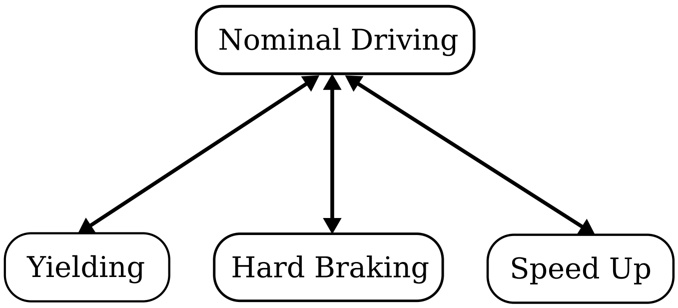

Fig. 3. Schematic of hybrid control structure.

The controller remains in the driving mode unless the pedestrian begins to enter the crosswalk while $d > 0$. To allow more time for the controller to respond, we allow the $\text{inCrosswalk}(x_p, \dot{x}_p)$ indicator function to be triggered the moment the pedestrian approaches the crosswalk from the sidewalk - e.g. once the pedestrian velocity $\dot{x}_p$ becomes non-zero.

Note that according to design constraint 1.b, the definition of entering the crosswalk will vary according to which of the fifty US states the vehicle is in. For example, in California, the pedestrian entering any portion of the crosswalk should trigger the control mode to change - while in Louisiana, the pedestrian entering the same half of the roadway as the vehicle should trigger the change [**?**].

Once the pedestrian enters the crosswalk, the algorithm decides which mode to enter next.

1) Time Advantage: Frequently he vehicle will pass through the intersection well before the pedestrian will reach the vehicle's lane. Assuming the vehicle is operating in a US state where stopping is not explicitly required, design constraint 2.a suggests it is desirable for the vehicle to continue through the intersection.

This can be formalized by calculating the *time advantage* $t_a dv$, also known as the *time to collision* as follows:

$$t_{adv} = \frac{d}{\dot{d}} - \frac{x_v - x_p}{\dot{x_p}} \tag{4}$$

Where x_v is the x position of the vehicle in the crosswalk. The control algorithm in this work will explicitly allow the vehicle to continue driving through the intersection as long as t_{adv} exceeds a specfiied threshold t_{max}.

2) Yielding: If the time advantage is not sufficient for the vehicle to pass through, the autonomous vehicle must slow down. The preferred option to meet design constraint 3.a is to brake at a low, comfortable deceleration $-a_{cmf}$ for the passenger. Note that design constraint 3.b is satisfied by having $d = 0$ be defined to be a point several meters ahead of the crosswalk.

Comfortable braking at a deceleration $-a_{cmf}$ is possible if sufficient braking distance exists. The braking distance is derived kinematically as

$$d_{brake} = \frac{\dot{d}^2}{2a_{cmf}} \tag{5}$$

If this holds true when the pedestrian starts to enter the crosswalk, the car enters a $Yielding$ state.

3) Hard Braking: In the unlikely event a pedestrian begins to cross when the time gap is low (e.g. under 3 seconds), the vehicle will need to prioritize design constraint 1.a and come to a stop at a deceleration higher than $-a_{cmf}$. This occurs when the following conditions holds:

$$\frac{\dot{d}}{2a_{max}} < d < \frac{\dot{d}^2}{2a_{cmf}} \tag{6}$$

Where a_{max} is the largest deceleration magnitude allowed by the tire-road friction.

B. Speeding Up

As a final condition, consider the case where the pedestrian enters the crosswalk just as the vehicle is crossing $d = 0$ - in this case, it makes little sense to decelerate, as the vehicle has insufficient space to stop before the crosswalk and will risk being rear-ended (Design Constraint 2.a) or stopping in the crosswalk. It makes more sense in this condition for the vehicle to speed up and exit the crosswalk quickly. As a result, if $d < \frac{\dot{d}}{2a_{max}}$, the vehicle speeds up.

C. Yielding

In the yielding state, the vehicle follows a different version of the feedback-feedforward dynamics. The vehicle first follows the speed limit until it reaches the critical value of $\frac{\dot{d}^2}{2a_{cmf}}$. In practice, an additional term $t_d elay\dot{d}$ is added to compensate for the delay in brake communication.

At the critical istance, the vehicle decelerates at the uniform yielding deceleration of $-a_{cmf}$, with an additional feedback term $k_s(\dot{d} - \dot{d}_d es)$, where $\dot{d}_d es$ is the desired velocity. The feedback term helps bring the vehicle speed to 0 at the desired stopping point.

The desired velocity profile $\dot{d}(d)$ for a vehicle decelerating at constant acceleration is given via integration:

$$\dot{d}(d) = \sqrt{2a_{cmf}(d - d_o) + \dot{d}_o^2} \tag{7}$$

Where d_o and $\dot{d}_o$ is the value of d and $\dot{d}$ when the controller first enters the yielding state. Simple inspection shows that the desired velocity is $\dot{d}_o$ when $d = d_o$ and is 0 when $d = 0$ (recall that we enter the yielding state when $d_o = \frac{\dot{d_o}^2}{2a_{cmf}}$.

The controller exits the yielding mode and returns to the driving mode once the pedestrian clears the crosswalk.

D. Hard Braking

In the hard braking state, the vehicle follows a similar feedback-feedforward algorithm, but the desired feedforward deceleration in this case is given by $\ddot{d} = -\frac{\dot{d}^2}{2d}$. Integrating to find the desired speed profile $\dot{d}(d)$ yields the following deceleration:

$$\dot{d}(d) = \frac{\dot{d}_o}{\sqrt{d_o}}\sqrt{d} \tag{8}$$

Where d_o and $\dot{d}_o$ is the value of d and $\dot{d}$ when the controller first enters the braking state. Again, the controller exits the braking mode and returns to the driving mode once the pedestrian clears the crosswalk.

E. Speed Up

In the speed up state, there is no need to follow an exact speed profile as the vehicle is merely trying to exit the crosswalk area slightly faster. In this case, the commanded acceleration $\ddot{d} = a_{cmf}$ until the pedestrian clears the crosswalk.

IV. Evaluation Methodology and Simulation Results

A. Evaluation Methodology

In order to check performance of the algorithm, both simulation and experimental studies were undertaken. The simulation results focused on testing Algorithm 1 against the design requirements from Table II-C over many pedestrian crossings.

The algorithm is validated in simulation via a crosswalk simulation environment developed in Python by the authors. The simulation environment is built on the ROS [**?**] robotics interface to enable easy porting of the control architecture to the experimental vehicle in V. The simulation includes features such as multiple lanes, the pedestrian crossing on the right or the left, and animation capabilities.

To simulate random pedestrian crossing events, a pedestrian is spawned in an area near the crosswalk. The pedestrian accepts a randomly sized time gap in the traffic stream to cross the road at constant speed $\dot{x}_p$. The size of the time gap is drawn from a normal distribution with mean μ_{gap} and standard deviation σ_{gap}. Statistics for μ_{gap} and σ_{gap} are obtained from a video graphic analysis by Feliciani et al. [23].

The ego vehicle's response to the pedestrian is simulated over Algorithm 1 for the parameters shown in Table I.

TABLE I
Simulation and Controller Parameters

Parameter	Symbol	Value	Units
Number of lanes	n	4	-
Gap variance	σ_{gap}	2.5	sec
Mean accepted gap	μ_{gap}	4.0	sec
Speed feedback gain	k_s	2.0	1 / sec
Brake time delay	t_{delay}	0	sec
Speed limit	$v_{\text{speedlimit}}$	4.5	m/s
Comfort acceleration	a_{cmf}	2	m/s^2
Maximum acceleration	$a_{\max}$	9	m/s^2

B. Simulation Results

V. Experimental Results

VI. Conclusions

Appendix

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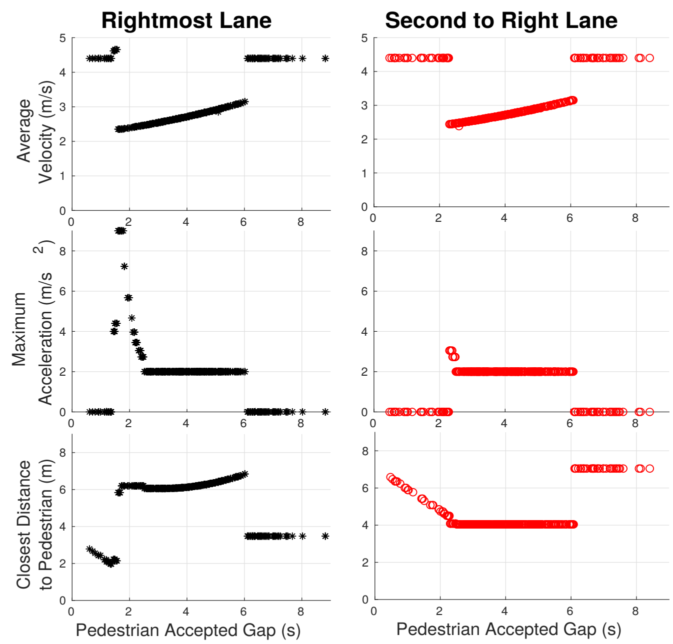

Fig. 4.

Acknowledgment

References

[1] D. J. Fagnant and K. Kockelman, "Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations," *Transportation Research Part A: Policy and Practice*, vol. 77, pp. 167–181, 2015. [Online]. Available: http://dx.doi.org/10.1016/j.tra.2015.04.003

[2] Matt Richtel and Conor Dougherty, "Google's Driverless Cars Run Into Problem: Cars With Drivers," 2015. [Online]. Available: https://www.nytimes.com/2015/09/02/technology/personaltech/google-says-its-not-the-driverless-cars-fault-its-other-drivers.html?_r=2

[3] N. Highway Traffic Safety Administration and Department of Transportation, "TRAFFIC SAFETY FACTS 2016 Fatal Motor Vehicle Crashes: Overview," no. October, pp. 1–9, 2016. [Online]. Available: https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812456

[4] C. G. Keller and D. M. Gavrila, "Will the pedestrian cross? A study on pedestrian path prediction," *IEEE Transactions on Intelligent Transportation Systems*, vol. 15, no. 2, pp. 494–506, 2014.

[5] I. Batkovic, M. Zanon, N. Lubbe, P. Falcone, and S. Y. Mar, "A Computationally Efficient Model for Pedestrian Motion Prediction."

[6] M. Koschi, C. Pek, M. Beikirch, and M. Althoff, "Set-Based Prediction of Pedestrians in Urban Environments Considering Formalized Traffic Rules," *Itsc*, 2018. [Online]. Available: http://mediatum.ub.tum.de/doc/1454223/540699586087.pdf

[7] V. Karasev, A. Ayvaci, B. Heisele, and S. Soatto, "Intent-aware long-term prediction of pedestrian motion," in *Proceedings - IEEE International Conference on Robotics and Automation*, vol. 2016-June, 2016, pp. 2543–2549.

[8] B. J. Schroeder and N. M. Rouphail, "Event-Based Modeling of Driver Yielding Behavior at Unsignalized Crosswalks," *Journal of Transportation Engineering*, vol. 137, no. 7, pp. 455–465, 2011. [Online]. Available: http://ascelibrary.org/doi/10.1061/%28ASCE%29TE.1943-5436.0000225

[9] B. Raghuram Kadali and V. Perumal, "Pedestrians' Gap Acceptance Behavior at Mid Block Location," *International Journal of Engineering and Technology*, vol. 4, no. 2, pp. 158–161, 2012. [Online]. Available: http://www.ijetch.org/show-42-241-1.html

[10] G. Yannis, E. Papadimitriou, and A. Theofilatos, "Pedestrian gap acceptance for mid-block street crossing," *Transportation Planning and Technology*, vol. 36, no. 5, pp. 450–462, 2013.

[11] D. Sun, S. V. Ukkusuri, and R. F. Benekohal, "Modeling of motorist-pedestrian interaction at uncontrolled mid-block crosswalks," *Transportation Research Record*, vol. Urbana, 51, no. November 2002, p. 61801, 2002.

[12] C. Lee and M. Abdel-Aty, "Comprehensive analysis of vehicle-pedestrian crashes at intersections in Florida," *Accident Analysis and Prevention*, vol. 37, no. 4, pp. 775–786, 2005.

[13] A. Rasouli and J. K. Tsotsos, "Autonomous Vehicles that Interact with Pedestrians : A Survey of Theory and Practice," pp. 1–18.

[14] D. Rothenbucher, J. Li, D. Sirkin, B. Mok, and W. Ju, "Ghost driver: A field study investigating the interaction between pedestrians and driverless vehicles," *25th IEEE International Symposium on Robot and Human Interactive Communication, RO-MAN 2016*, pp. 795–802, 2016.

[15] M. Matthews, G. V. Chowdhary, and E. Kieson, "Intent Communication between Autonomous Vehicles and Pedestrians."

[16] T. Lagström and V. M. Lundgren, "AVIP - Autonomous vehicles interaction with pedestrians An investigation of pedestrian-driver communication and," p. 84, 2015.

[17] F. Camara, R. Romano, G. Markkula, R. Madigan, N. Merat, and C. Fox, "This is a repository copy of Empirical game theory of pedestrian interaction for autonomous vehicles . White Rose Research Online URL for this paper : Version : Accepted Version Proceedings Paper : orcid . org / 0000-0003-0244-1582 et al . (3 more author," 2018.

[18] B. Chen, D. Zhao, and H. Peng, "Evaluation of Automated Vehicles Encountering Pedestrians at Unsignalized Crossings."

[19] T. Bandyopadhyay, C. Z. Jie, D. Hsu, H. Marcelo, A. Jr, D. Rus, and E. Frazzoli, "Intention-Aware Pedestrian Avoidance."

[20] S. M. Thornton, "AUTONOMOUS VEHICLE MOTION PLANNING WITH ETHICAL CONSIDERATIONS," Ph.D. dissertation, 2018.

[21] L. E. Di Pietro, Charles M and King, "Pedestrian Gap Acceptance," *Highway Research Record*, no. 308, 1970.

[22] S. Schmidt and B. Färber, "Pedestrians at the kerb - Recognising the action intentions of humans," *Transportation Research Part F: Traffic Psychology and Behaviour*, 2009.

[23] C. Feliciani, L. Crociani, A. Gorrini, G. Vizzari, S. Bandini, and K. Nishinari, "A simulation model for non-signalized pedestrian crosswalks based on evidence from on field observation," *Intelligenza Artificiale*, vol. 11, no. 2, pp. 117–138, 2017. [Online]. Available: http://www.medra.org/servlet/aliasResolver?alias=iospress&doi=10.3233/IA-170110