

# 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 through extensive simulation, 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 significant 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 fatalities 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 on 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 focuses on pedestrian behavior analysis using empirical data, typically in the form of video analysis. While typically studied for purposes of road design, this body of literature holds promising insights for AV designers. For example, Schroeder and Roupail [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 Sun et al. [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 Rasouli et al. [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. To improve the issue of trust, several researchers have also developed external communication interfaces to more clearly broadcast the intent of the autonomous vehicle ([15], [16]).

One issue with automated driving for crosswalk scenarios is that an overly conservative crossing algorithm will often be taken advantage of or cause confusion among pedestrians [17]. Camara et al. [17] attempted to model the natural negotiation for priority between a pedestrian and an AV at an intersection using the framework of game theory. Chen et al. [18] notes the need for a tradeoff between passive and aggressive driving behavior, and developed a stochastic model of pedestrian behavior to evaluate proposed AV control policies. Control policies for pedestrian interaction are also developed in [19], who proposes a Mixed-observable Markov Decision Process (MOMDP) to incorporate the intention uncertainty of a pedestrian. A Partially-observable Markov Decision Process (POMDP) formulation is also proposed by Thornton [20], who proposes a value-

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sensitive design framework to assist with the development of engineering specifications for the control algorithm.

### 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 hybrid 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 controller modes. Finally, experimental results are shown on a real vehicle to demonstrate the feasibility of the proposed controller in real-time.

## 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 lights and walk signals guide the interaction of vehicles and pedestrians explicitly. Fig. 1 shows the latter example, in which there is no such control device, and 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 in. 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 [21].

### B. Problem Formalization

A diagram of the relevant state variables is shown in Fig. 1. 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

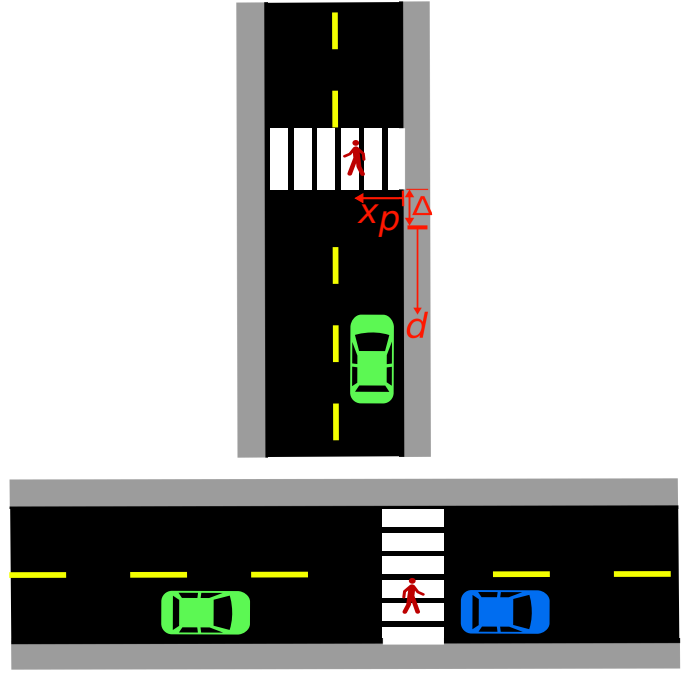


Fig. 1. Top: Description of relevant problem variables. Bottom: Schematic of pedestrian approaching a stream of traffic at a mid-block intersection. Ego vehicle shown in green. We develop a hybrid control framework for the green vehicle, which considers the distance ( $d$ ) to a stopping point  $\Delta$  ahead of the crosswalk and the pedestrian’s position in the crosswalk ( $x_p$ ).

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:

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

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 occupants, 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.

### C. System Requirements

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

Engineering Specification[20]	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 acceleration: Nominal brake and acceleration limits of 2 m/s <sup>2</sup>

#### D. Pedestrian Gap Acceptance

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

$$\text{gap} = \frac{\text{distance to crosswalk}}{\text{vehicle speed}} \quad (2)$$

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 its 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 [22], and are very likely to cross when they have more than seven seconds [23].

### III. PROPOSED CONTROL ARCHITECTURE

The proposed control architecture is shown in Fig. 2, 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 modes the controller is in. The next section will describe the four modes.

TABLE I  
PARAMETERS FOR ALGORITHM 1

Symbol	Definition
$d_{\max}$	$\frac{\dot{d}^2}{2a_{\max}}$
$d_{\text{cmf}}$	$\frac{\dot{d}^2}{2a_{\text{cmf}}}$

#### 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:

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

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

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```

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

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

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

if state = SPEED UP then
   $\ddot{d} = a_{\text{cmf}}$ 
  if not inCrosswalk( $x_p$ )  $\vee d < 0$  then
    state ← DRIVING
  end if
end if
end while

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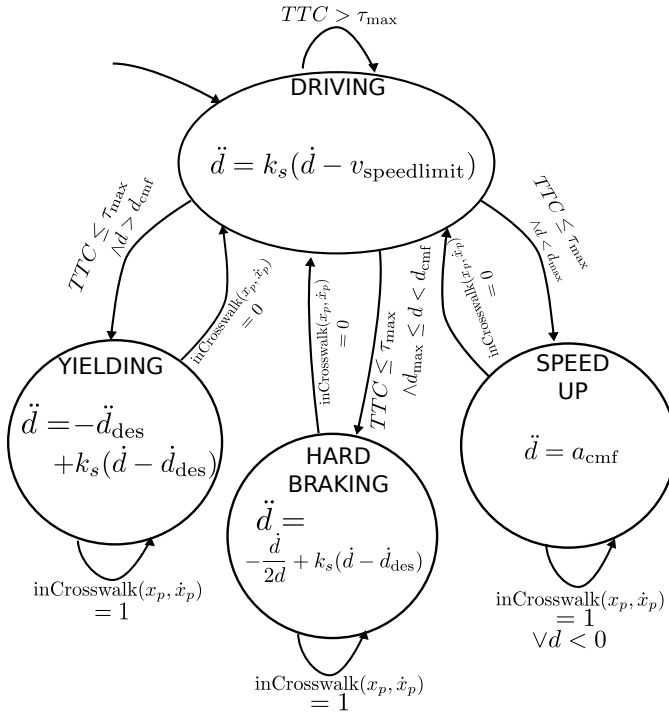


Fig. 2. Schematic of hybrid control structure.

The controller remains in the driving mode unless the pedestrian begins to enter the crosswalk before the vehicle has passed. In this case, we mathematically define “beginning to enter” as the instant the pedestrian begins moving towards the crosswalk, even if the pedestrian is currently on the sidewalk:

$$\text{inCrosswalk}(x_p, \dot{x}_p) = \begin{cases} 1 & : \dot{x}_p \neq 0 \vee 0 \leq x_p \leq x_F \\ 0 & : \text{otherwise} \end{cases} \quad (4)$$

Where  $x_F$  is the end of the crosswalk area of interest. Note that according to design constraint 1.b, the definition of  $x_F$  will vary according to which US state the vehicle is in. For example, in California,  $x_F$  would be at the end of the crosswalk, while in Louisiana,  $x_F$  would just be the same half of the crosswalk as the vehicle [21].

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

**1) Time Advantage:** Frequently the 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*  $t_{\text{adv}}$ , also known as the *time to collision* as follows:

$$t_{\text{adv}} = \frac{d}{\dot{d}} - \frac{x_v - x_p}{\dot{x}_p} \quad (5)$$

Where  $x_v$  is the  $x$  position of the vehicle in the crosswalk. Algorithm 1 explicitly allows the vehicle to continue driving

through the intersection as long as  $t_{\text{adv}}$  exceeds a specified threshold  $t_{\text{max}}$ .

**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  $-a_{\text{cmf}}$  for the passenger.

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

$$d_{\text{brake}} = \frac{\dot{d}^2}{2a_{\text{cmf}}} \quad (6)$$

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

**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  $-a_{\text{cmf}}$ . This occurs when the following conditions holds:

$$\frac{\dot{d}^2}{2a_{\text{max}}} < d < \frac{\dot{d}^2}{2a_{\text{cmf}}} \quad (7)$$

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

**4) 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 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  $d < \frac{\dot{d}}{2a_{\text{max}}}$ , the vehicle speeds up.

## B. 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  $\frac{\dot{d}^2}{2a_{\text{cmf}}}$ . In practice, an additional term  $t_{\text{delay}}\dot{d}$  is added to compensate for the delay in brake communication.

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

The desired velocity profile  $\dot{d}_{\text{des}}(d)$  for a vehicle decelerating at constant acceleration is given by:

$$\dot{d}_{\text{des}}(d) = \sqrt{2a_{\text{cmf}}(d - d_o) + \dot{d}_o^2} \quad (8)$$

Where  $d_o$  and  $\dot{d}_o$  are the values of  $d$  and  $\dot{d}$  when the controller first enters the yielding state. 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  $d_o = \frac{\dot{d}_o^2}{2a_{\text{cmf}}}$ ).

The controller exits the yielding mode and returns to the driving mode once the pedestrian clears the crosswalk (e.g. once  $x > x_F$  in (4)).

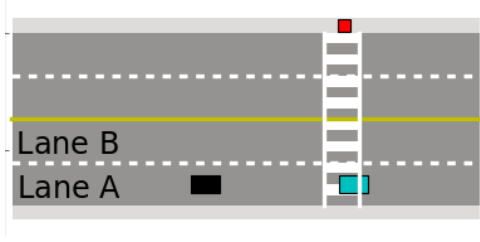


Fig. 3. Crosswalk simulation environment for algorithm validation. Ego vehicle is shown in black, leading vehicle in traffic stream shown in blue, and pedestrian shown in red.

### C. 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  $\dot{d}_{\text{des}}(d)$  yields the following deceleration:

$$\dot{d}_{\text{des}}(d) = \frac{\dot{d}_o}{\sqrt{d_o}} \sqrt{d} \quad (9)$$

Where  $d_o$  and  $\dot{d}_o$  are the values 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.

### D. 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 is  $\ddot{d} = a_{\text{cmf}}$  until the pedestrian clears the crosswalk or once the vehicle passes the stopping location (i.e.  $d < 0$ ).

## 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 specified design requirements over many pedestrian crossings.

The algorithm is validated in simulation via a built-from-scratch crosswalk simulation environment (Fig. 3) developed in Python. The simulation environment is built on the ROS robotics interface to enable easy porting of the control architecture to the experimental vehicle in Section V. The simulation includes features such as customizable lanes, the pedestrian crossing on the right or the left, and animation capabilities.

To simulate random pedestrian crossing events, a pedestrian is spawned on the sidewalk near the entrance to the crosswalk. The pedestrian accepts a randomly sized time gap in the traffic stream to cross the road at constant speed  $\dot{x}_p$ . While pedestrian speeds vary both according to demographic factors and within an individual crossing attempt [24], the

primary focus of this study is varying the gap acceptance, and a constant velocity for all trials is therefore assumed.

The size of the time gap is drawn from a normal distribution with mean  $\mu_{\text{gap}}$  and standard deviation  $\sigma_{\text{gap}}$ . Statistics for  $\mu_{\text{gap}}$  and  $\sigma_{\text{gap}}$  are obtained from results of the video graphic analysis by Feliciani et al. [24].

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

TABLE II  
SIMULATION AND CONTROLLER PARAMETERS

Parameter	Symbol	Value	Units
Number of lanes	$n$	4	-
Gap variance	$\sigma_{\text{gap}}^2$	2.5	sec
Pedestrian velocity	$\dot{x}_p$	1.2	m/s
Mean accepted gap	$\mu_{\text{gap}}$	4.0	sec
Safety offset	$\Delta$	5.0	m
Speed feedback gain	$k_s$	2.0	1 / sec
Brake time delay	$t_{\text{delay}}$	0	sec
Speed limit	$v_{\text{speedlimit}}$	4.5	m/s
Comfort acceleration	$a_{\text{cmf}}$	2	m/s <sup>2</sup>
Maximum time advantage	$t_{\text{max}}$	4	sec
Maximum acceleration	$a_{\text{max}}$	9	m/s <sup>2</sup>

### B. Simulation Results

Figure 4 shows simulation results for the case where the pedestrian enters the crosswalk on the same side of the road as the vehicle. The left column of the figure is for the case where the vehicle is on the right-most lane of a four way road (marked "Lane A"), while the right column of the figure is for the case where the vehicle is in the second to right lane (Lane B). Every marker in the figure represents one of 750 simulated vehicle crossings.

Figure 5 shows the same simulation results, but for the case where the pedestrian enters the crosswalk on the opposite side of the road as the vehicle. Again, the total number of pedestrian crossing trials conducted was 750, with 375 trials for each side.

1) *Safety and Legality*: To meet the collision avoidance design requirement, we generated enough simulations to ensure errant pedestrian crossing behavior at "risky" accepted gaps ( $< 3$  seconds). The minimum distance between the vehicle and the pedestrian for each trial is shown in (a) and (b) of Figures 4 and 5. The vehicle is able to maintain a safe distance of at least four meters from the pedestrian for the case where the vehicle is Lane B. This is because the algorithm has enough time to react to a pedestrian crossing no matter what size gap is accepted.

The riskiest case occurs when the vehicle is in Lane A and the pedestrian crosses from the right side, accepting a gap between 1.25 and 1.75 seconds. Note that this is in general unlikely given gap acceptance statistics reported in the literature [13][24], but would represent a safety risk given the vehicle has limited time to react. However, since the algorithm recognizes that braking will not clear the crosswalk, the vehicle is able to speed up and maintain at least 2 meters of lateral distance from the pedestrian at all times. Note that a better way to confirm robustness of the

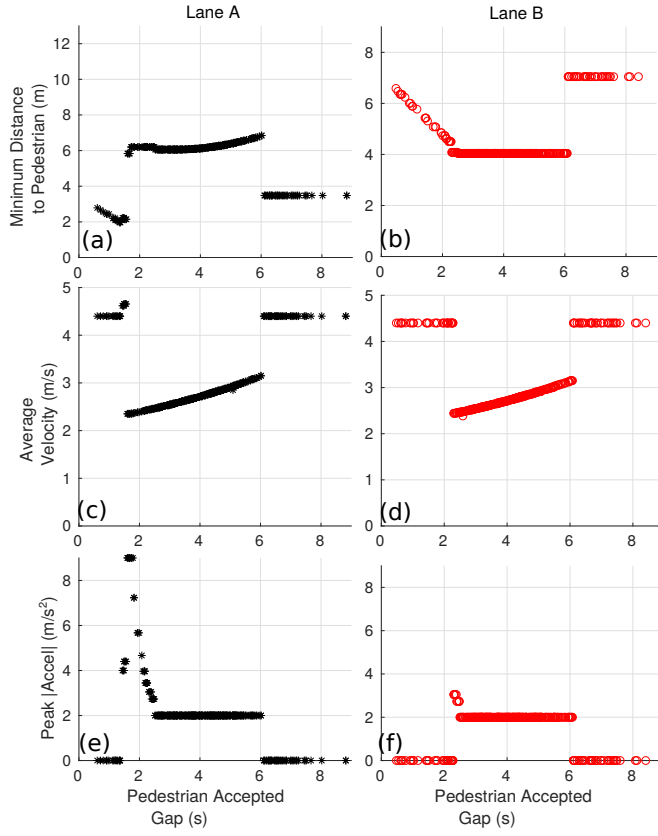


Fig. 4. Simulation results for case where pedestrian enters the crosswalk on the same side of the road as the vehicle. Plots (a) and (b) show the closest distance between the vehicle and pedestrian for each crossing trial, (c) and (d) plots the average vehicle velocity for each simulated crossing, and (e) and (f) plots the peak acceleration / deceleration magnitude for each trial.

controller to all reasonable pedestrian behaviors would be through a theoretical verification analysis - this will be the focus of future work.

In terms of the fifty state legality requirement, we conducted our simulation for the twenty states where the vehicle is required to yield, not stop, to a pedestrian in the same side of the crosswalk or approaching from the opposite side. For the US states where the vehicle is explicitly required to stop, the change to the controller is trivial - the controller may not stay in the driving mode if sufficient time advantage exists (see Algorithm 1).

2) *Efficiency*: The requirement to minimize deviation from speed of traffic is validated in (c) and (d) of Figures 4 and 5, which shows the average velocity of the vehicle for each simulated crossing. For high accepted gaps, the pedestrian simply waits for the ego vehicle to exit the crosswalk before beginning to walk, and the algorithm does not need to slow down from the speed of traffic. For low accepted gaps, the vehicle cannot stop, and must speed up or continue driving through the intersection, also keeping the vehicle speed high.

The most disruption to traffic flow occurs when the vehicle must slow down significantly or stop, which occurs for

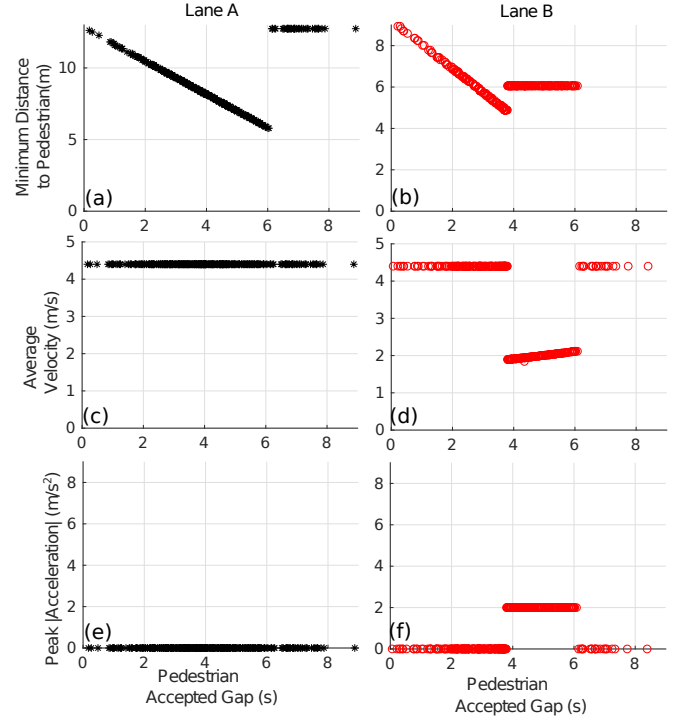


Fig. 5. Simulation results for case where pedestrian enters the crosswalk on the opposite side of the road as the vehicle. Plots (a) and (b) show the closest distance between the vehicle and pedestrian for each crossing trial, (c) and (d) plots the average vehicle velocity for each simulated crossing, and (e) and (f) plots the peak acceleration / deceleration magnitude for each trial.

accepted gaps between 2-6 seconds. In this case, the average velocity increases as the accepted gap increases. Larger accepted gaps give the pedestrian more time to walk before the vehicle approaches, meaning they are closer to exiting the crosswalk when the vehicle must yield. This means the vehicle does not need to stop for as much time, resulting in higher average velocity.

Note that a special case occurs in Fig. 5 where the vehicle is in Lane A and the pedestrian crosses from the opposite side of the road. Because the vehicle is at a far distance from the pedestrian, the time advantage remains sufficiently high for the vehicle to comfortably continue through the crosswalk without needing to slow down.

Table III shows a summary of the average speed compared to the baseline speed of 4.4 m/s for each of the four cases.

TABLE III AVERAGE VEHICLE SPEED			
Pedestrian Entry	Vehicle Lane	Average Speed (m/s)	Pct. of Baseline
Right Side	Right-Most	2.90	66%
Right Side	Second-to-Right	2.93	67%
Left Side	Right-Most	4.4	100%
Left Side	Second-to-Right	2.80	64%

3) *Smoothness*: The requirement of keeping a low acceleration magnitude where possible is validated through (e) and (f) of Figures 4 and 5, which plots the peak acceleration



/ deceleration magnitude for each simulated crossing. The vehicle is able to maintain a peak acceleration of  $2 \text{ m/s}^2$  for the vast majority of simulated trials, particularly when the pedestrian crosses from the opposing side of the road or when the vehicle is in the second to right line.

However, there are a handful of simulated trials in Fig. 4 when the pedestrian accepts a gap between 1.75-2.5 seconds and the vehicle is in Lane A. In this case, the vehicle must enter the *Hard Braking* state and decelerate at a magnitude higher than  $a_{\text{cmf}}$ . This is required in order to meet the collision avoidance constraint, which naturally takes priority. Again, note that this situation occurs relatively rarely, as pedestrians typically accept gaps between 3-6 seconds and are unlikely to risk hazardous behaviors unless distracted.



Fig. 6. Hyundai Genesis G80 experimental testbed.



Fig. 7. Two lane crosswalk used for experimental testing.

## V. EXPERIMENTAL RESULTS

The proposed hybrid controller is tested experimentally using a Hyundai Genesis G80 experimental testbed, shown in Fig. 6. A two lane unsignalized intersection at Richmond Field Station near Berkeley's campus was chosen for the experimental validation (Fig. 7). In lieu of an actual pedestrian, a pedestrian was simulated virtually using the ROS simulation architecture, with the position of the pedestrian passed to the vehicle controller in real time. Differential GPS was used to record the distance to the crosswalk, and a steering controller from [25] was used to autonomously steer the vehicle down the road. Relevant parameters of the experiments are shown below in Table IV.

Several key differences to highlight between the simulations and the experiments are that the number of lanes is

TABLE IV  
EXPERIMENTAL PARAMETERS

Parameter	Symbol	Value	Units
Number of lanes	$n$	2	-
Safety offset	$\Delta$	5	m
Speed feedback gain	$k_s$	1.0	1 / sec
Brake time delay	$t_{\text{delay}}$	0.5	sec
Speed limit	$v_{\text{speedlimit}}$	7	m/s
Comfort acceleration	$a_{\text{cmf}}$	2	$\text{m/s}^2$
Maximum time advantage	$t_{\text{max}}$	4	sec
Maximum acceleration	$a_{\text{max}}$	9	$\text{m/s}^2$

decreased from 4 to 2 and that the speed limit is increased to 7 m/s to match the parameters of the experimental intersection. The experiment consisted of six trials intended to show operation of the four discrete modes of the controller. A description of the trial parameters are shown in Table V.

TABLE V  
EXPERIMENTAL PARAMETERS

Trial Number	Gap Accepted (sec)	Pedestrian Entry	Mode
1	4.0	right	Yield
2	1.0	right	Speed Up
3	7.0	right	Yield
4	2.5	right	Hard Brake
5	3.0	left	Yield
6	1.0	left	Speed Up

The experimental velocity and acceleration is plotted vs  $d$  in Figure 8. In Trial 1, the virtual pedestrian accepts a gap of four seconds, giving the vehicle enough time to yield at a deceleration of  $2 \text{ m/s}^2$ . Note that the low level acceleration controller exhibits a large time delay between commanded and actual acceleration. Because this is accounted for in Algorithm 1, the vehicle is able to brake early and the vehicle is stopped right at  $d = 0$  before the pedestrian exits the crosswalk and the vehicle speeds back up.

In Trial 2, the pedestrian enters from the right with just 1 second before collision. This experiment, while unlikely in reality, was undertaken to verify the vehicle would not brake, but accelerate through the intersection. Trial 3 represents a situation where the pedestrian crosses with a large (7 second) gap. In this case, the pedestrian has enough time to almost cross before the vehicle needs to yield, resulting in the vehicle only needing to slow down slightly.

In Trial 4, the pedestrian exhibits risky behavior, crossing with a 2.5 second gap. In this case, the vehicle has enough time to brake, but must decelerate rapidly at  $5 \text{ m/s}^2$  in the *hard braking* mode. Given the brake delay in the experimental vehicle, significant overshoot occurs, and the vehicle stops nearly 2.5 meters ahead of the desired stopping location. However, given that the desired stop location is 5 meters ahead of the crosswalk, this is sufficient to avoid a collision. Note that unlike in the yielding mode, the brake delay can not be compensated for because the pedestrian enters unexpectedly.

Trials 5 and 6 represent pedestrian crossings from the opposite side of the road under accepted gaps of 3.0 and 1.0 seconds, respectively. In the former case, the vehicle is

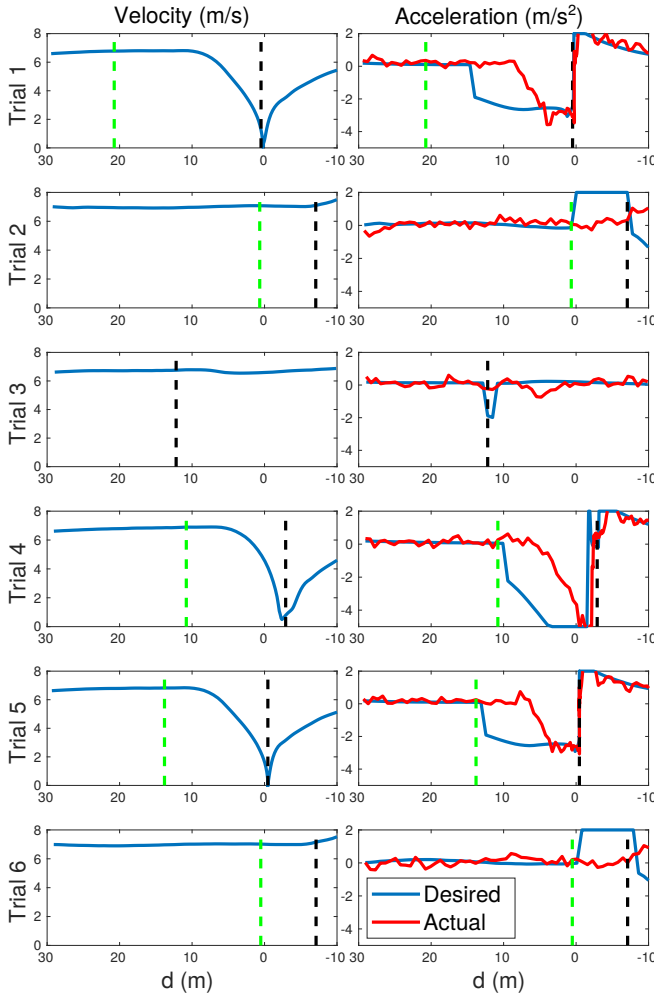


Fig. 8. Experimental velocity and acceleration plotted vs distance to crosswalk. Green lines mark the point where the pedestrian first enters crosswalk. Black lines mark the point where the pedestrian leaves the crosswalk. Note that for Trial 3, the green line is off the page at 40 meters.

able to yield in a fashion similarly to Trial 1, and in the latter case, the vehicle is able to speed through the intersection, as in Trial 2.

## VI. CONCLUSIONS

This paper proposes a novel hybrid control architecture for determining closed loop vehicle control at an unsignalized intersection. Through simulation, we show that the system ensures safety across a continuous spectrum of pedestrian gap acceptance behaviors, while balancing the competing demands of smoothness for the vehicle occupants and limited traffic slowdown for other vehicles in the traffic stream. Remarkably, with just four distinct modes, the controller is able to handle multiple lanes and pedestrians crossing from either side of the road. Further work will focus heavily on integrating perception to accurately determine when to trigger switches in the controller modes, as determining pedestrian intent to cross is a major input required for the controller.

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