Improving Safety of Vulnerable Road Users: Effectiveness of Environment and In-Vehicle Warning Systems at Intermodal Interchanges

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ABSTRACT

In 2009, there were over 114,000 fatalities and injuries in the U.S. among vulnerable road users (VRUs; pedestrians and pedal cyclists; NHTSA, 2010). 4,092 pedestrians were killed in pedestrian-vehicle crashes. Pedestrian risk at intermodal interchanges such as bus terminals may be due to factors such as the greatly increased number of pedestrians, the increased likelihood of poor pedestrian behavior, and the lack of separation between pedestrians and vehicles (Clifton & Kreamer-Fults, 2007; Zegeer & Bushell, 2012). The current study investigates the effectiveness of structural and in-vehicle interventions for modifying driver behavior as drivers approach, pass through, and depart from an urban bus terminal. The impact of facility structural elements (pedestrian crossing signs, marked crosswalks, and sidewalks) and an in-vehicle pedestrian warning system was evaluated using the Center for Advanced Vehicular Systems driving simulator. 37 participants completed 186 drives in the driving simulator. Driver speed and lane position were evaluated. An in-vehicle alarm indicating "high pedestrian areas" led to reduced driver speed but drivers shifted closer to the shoulder (and pedestrians). Marked crosswalks had no observed effect on driver speed or vehicle controls but also led to drivers positioning themselves closer to the shoulder. Drivers exhibited risk compensation behaviors by driving faster and closer to shoulders when sidewalks were present. Pedestrian crossing signals led to reduced driver speed.

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INTRODUCTION

In the United States in the year 2009, there were over 114,000 fatalities and injuries among vulnerable road users (VRUs; pedestrians and pedal cyclists; NHTSA, 2010). 4092 pedestrians were killed in pedestrian-vehicle crashes. 630 pedal cyclists were killed in cyclist-vehicle crashes.

Previous research has identified many factors that affect risk of injury and fatality for vulnerable road users. Inappropriate pedestrian behavior, poor driver behavior, and structural issues contribute to the risk to vulnerable road users. VRU risk at intermodal interchanges such as schools (Clifton & Kreamer-Fults, 2007) and bus stops may be due to factors such as the greatly increased number of pedestrians, the increased likelihood of poor pedestrian behavior, and the lack of separation between pedestrians and vehicles (Zegeer & Bushell, 2012). While research has identified or proposed behavioral and engineering interventions to reduce risk, much of this research is based on macro-scale statistical models and not on actual analysis of human behavior in response to the interventions.

OBJECTIVE

The objective of the research effort is to investigate the effectiveness of structural and in-vehicle interventions for modifying driver behavior in order to increase the safety of vulnerable road users as drivers approach, pass through, and depart from intermodal interchanges**.** A 2x2x2x2 repeated measures mixed design was be used to evaluate the effect of facility structural elements (within-subjects: 8 designs; 2 (traffic signals) x 2 (marked crosswalks) x 2 (sidewalks)) and the effect of an in-vehicle VRU warning system (between-subjects: 2 levels). Members of the general public in and around Mississippi State University were be recruited to drive through simulated urban areas in a high-fidelity driving simulator. During the simulated drives, they drove through small urban areas that include an intermodal interchange facility (i.e. bus terminal). At these facilities, almost all users are pedestrians during at least one leg of their trip. During the pedestrian leg, the pedestrians are at risk as they may be required to move across and along roadways containing fast moving vehicles. As the driver passes a facility, the driver was expected to monitor and respond to the actions of simulated VRUs while focused on a primary search task. The structural elements associated with these interchanges varied (i.e. presence of traffic signals, presence of marked crosswalks, and presence of sidewalks). In addition to structural element variation, some drivers were equipped with an in-vehicle two-stage warning system that will provide a cautionary warning when approaching an area that may be high risk for VRUs and an imminent crash warning when an impending collision between a VRU and the vehicle is detected.

This research provides a micro-scale understanding of how drivers respond to specific environmental changes that are designed to improve safety. We are particularly interested in the possibility that some interventions may actually increase risk to VRUs. For example, presence of marked crosswalks may create an expectation in the driver that all pedestrians will cross at the marked location and increase the risk of collision with a pedestrian that chooses to dart across mid-block.

This research directly affects vulnerable road user safety by identifying the most effective interventions for improving driver behavior near intermodal interchanges. The results affect structural environment design decisions and ultimately will save lives.

SCOPE

In 2009, 4722 vulnerable road users (4092 pedestrians and 630 cyclists) were killed in vehicle crashes and 110,000 vulnerable road users (59,000 pedestrians and 51,000 cyclists) were injured (NHTSA, 2010). Vulnerable road users represent a relatively large 14% of the fatalities resulting from vehicle crashes. During 2009, 13% of pedal cyclists killed in traffic crashes were between the ages of 5 and 15. The majority (72%) of vulnerable road fatalities occur in urban environments. Many factors have been identified that affect the likelihood of pedestrian-vehicle crashes. These factors can be loosely categorized in three categories: pedestrian behaviors, driver behaviors, and environment elements.

Pedestrian Behaviors

Male pedestrians are much more likely than female pedestrians to be involved in a pedestrian-vehicle accident (NHTSA, 2010; Clifton, Burnier, & Akar, 2009). The involvement of alcohol and drugs also increases the likelihood of severe injury or death (Clifton, Burnier, & Akar, 2009). Nighttime accidents are more likely to result in serious injury. Pedestrians that wear dark clothing are actually less likely to be severely injured or killed, possibly because 70% of these accidents occur during the daytime (Clifton, Burnier, & Akar, 2009). A significant contributor to pedestrian risk is inappropriate pedestrian behavior including darting across mid-block, dashing across at intersections, not using crosswalks, and not complying with traffic signals (Clifton, Burnier, & Akar, 2009; FHWA, 1996).

Driver Behaviors

Driver behaviors can also increase the risk to vulnerable road users. As with pedestrians, involvement of alcohol or drugs increases the risk to vulnerable road users (Clifton, Burnier, & Akar, 2009). Motorcycles, trucks, vans, buses, and emergency vehicles are more likely to result in severe injury or fatality (Clifton, Burnier, & Akar, 2009).Vehicles traveling at higher speeds are likely to result in more severe injuries (Mueller, 1998). A 2011 analysis of driver behaviors in the SafetyNet Accident Causation System (SNACS) revealed that drivers would fail to observe a VRU either due to obstruction or distraction, incorrectly understanding the situation, or execute a poor plan for the maneuver being performed (Habibovic & Davidsson, 2011).

Environment Elements

In addition to pedestrian and driver behaviors, features of the environment have a significant effect on risk to VRUs. Some features are tied to global issues. For example, pedestrians are much more likely to be killed in a rural accident due to higher vehicle speeds, lack of separation between pedestrians and vehicles (walking along the roadway), and distance from emergency care (Mueller, 1988). In urban areas generally, and in specific urban locations such as schools (Harwood, Torbic, Gilmore, et al, 2008; Loukaitou-Sideris, Liggett, & Sung, 2007;

Clifton & Kreamer-Fults, 2007), shopping centers (Ossenbruggen, Pendharkar, & Ivan, 2001), and bus stops (Harwood, et al, 2008), crashes are more likely to occur because of the greater number of pedestrians and higher likelihood of inappropriate pedestrian behaviors. These locations are all intermodal in the sense that users of the facilities travel to the locations by car, bus, rail or bicycle and then switch to a pedestrian mode as they move across and along the same roadways as the vehicles to actually access the building(s) of interest.

Identified / Proposed Environment Solutions

Speed controls have been suggested (Retting, Fergunson, & Carter, 2003), but presence of speed controls have had mixed results (Graham & Galaister, 2003). Methods for separating vulnerable road users from vehicles have also been proposed including construction of sidewalks and walkways along roadways (Retting, Fergunson, & Carter, 2003) and creation of separate driveways into educational facilities (Clifton & Kreamer-Fults, 2007). Use of traffic control devices have also been proposed as potential solutions (Graham & Galaister, 2003; Ossenbruggen, Pendharkar, & Ivan, 2001). There is little research assessing how implementation of these interventions affects driver behavior.

In-vehicle Warning Systems

Many of the proposed environment solutions are designed to modify pedestrian behavior (moving them away from roadways) or require drivers to attend to other environment information (presence of traffic control devices and crosswalks). If drivers are already failing to detect and respond to VRUs in existing environments, the addition of new sources of information does not guarantee that the driver will observe the new information. Instead, a warning system could be placed within the vehicle with more direct options for capturing a driver’s attention. There are four types of in-vehicle systems: information support, warning and feedback, intervene, automated driving (Carsten & Nilsson, 2001).

Habibovic and Davidsson (2011) proposed a system that would combine general information when entering urban areas with high numbers of pedestrians and specific imminent warnings when an impending collision is detected. The warnings should be provided through an in-vehicle interface and the level of warning should be tied to the risk of crash. Crash risk should be calculated by identifying vulnerable road users, tracking their position and speed over time, and predicting the likelihood that the path of the vehicle and the VRU will intersect. Habibovic and Davidsson calculate that it will be necessary for the system to predict the next 3.2 seconds of driver behavior and the next 5 meters of travel for pedestrians and 13 meters of travel for bicyclists. The proposed research will implement an in-vehicle warning system based on Habibovic and Davidsson’s recommendations.

An in-vehicle warning system may be more likely to capture a driver's attention but it may create its own issues (Carsten & Nilsson, 2001). For example, the driver may come to rely on the in-vehicle warning system to identify vulnerable road users. This may lead drivers to reduce their visual scanning behavior, limit their field of view, and become less aware of vulnerable road users until the vehicle brings them to his/her attention at which point the driver may not have sufficient time or awareness to make effective decisions for response. Implementation and testing of an in-vehicle warning system is necessary to ensure that the overall safety of the traffic system is increased.

METHODOLOGY

Experimental Design

There were four independent variables analyzed in this study: crosswalks, sidewalks, signals, and the in-vehicle alarm technology (IVT). All of these had one of two conditions, either present or absent. Infrastructure variables (crosswalks, sidewalks, signals) were within subjects factors. IVT was a between subjects variable, with half of the participants driving with IVT present and half of the participants driving with IVT absent. Order of scenarios was determined using a balanced Latin square design (2x2x2) based on the three infrastructure variables (crosswalk, sidewalk, signals). Figure 1 shows the representation of the infrastructure variables in the simulator environment.

Figure 1: Infrastructure variables in the simulator environment

The dependent variables consisted of multiple performance variables collected by the simulator. These include velocity, throttle, brake, lane offset, and steering data. For each of these variables a maximum, minimum, and average value was calculated. Velocity was measure in meters per second but converted to miles per hour for data analysis. Throttle and brake pressures were measured anytime the gas pedal or brake pedal were engaged, respectively. The lane offset data is measure of departure from a center line in the middle of the lane. Position offsets to the left of this center line produces a negative value and offsets to the right produce positive numbers.

Participants

The participants for this study were recruited from the student population of Mississippi State University. Prior to the experiment, subjects were screened and required to have good vision, hearing, and no history of epilepsy or simulator/motion sickness. There were a total of 37 participants with a mean age of 19.7 (sd = 1.6). Subjects were required to have a valid driver's license in order to participate. The average age at which they received their driving license was 16.2(sd = 0.9). The participants were asked the average amount of driving they perform on a given day. 23 of them reported driving for 30 minutes or less. They were also asked how often they drive for more than an hour. 19 participants responded “once a month.” Participants were asked to complete the driving behavior questionnaire (DBQ), a series of questions pertaining to their driving characteristics. For example, they were asked how often do you check your speedometer and notice you are unknowingly speeding. The most frequent response to this was “occasionally.” When asked “how often do you take a chance and cross on lights that have turned red,” the most frequent response was “Never.” Another pertinent question addressed on the DBQ asked participants “when lost in thought or distracted, how often do you fail to notice someone waiting at a marked crossing, or crossing light that has just turned red.” The majority of participants responded “Hardly Ever” or “Never.”

Protocol

The population was notified of our study via posted flyers and word-of-mouth. In order to participate they first completed an online screening survey. The requirements for eligibility included: good vision, hearing, and no previous history of epilepsy or simulator/motion sickness. Following completion of the screening survey, a researcher then scheduled the participant’s experiment time.

For the experiment, two researchers were present: an operator for the driving simulator and an experimenter to direct and assist the participant. Upon the participant’s arrival, the participant was first given the consent form. After agreeing to the terms of the experiment, the participant was asked to sign and date the form. Next the participant completed a demographics survey, a driving behavior questionnaire (DBQ), and a baseline motion/simulator sickness questionnaire (MSSQ). Upon completion of the forms, the participant was then introduced to the driving simulator and given an overview of the simulation system and the simulator vehicle. Any questions were also answered at this time.

In an effort to eliminate modified driving behavior, the participants were given a task to complete during their drives. Participants were told that their task was to aid Mississippi State University’s marketing team by driving through the urban environments and searching for the MSU billboard in order to verify that the billboard had been put in place. Participants were shown pictures of the billboard prior to entering the simulator vehicle. Furthermore, examples of the billboard were placed throughout the familiarization drive in effort to help them recognize the billboard in the simulated environment. A sample image from the driving simulator environment is shown in Figure 1.

In total the experiment consisted of nine drives, including an initial familiarization drive. In the familiarization drive, participants were directed to explore an urban environment similar to the ones present in the data collecting drives. This drive allowed participants to become comfortable with how the simulator operated and lasted for approximately five minutes. The following eight data collection drives occurred in blocks of two. Order of scenarios was determined using a balanced Latin square design (2x2x2) based on the three infrastructure variables (crosswalk, sidewalk, signals).

In data collection drives, participants were directed to find the MSU billboard and then exit the city. During the search for the MSU billboard, drivers would pass by simulated bus terminals. All bus terminal streets were “high pedestrian areas” and included pedestrians walking parallel to the roadway on the opposite side of the street to the driver on the near side of the terminal and on both sides of the street on the far side of the terminal. As the driver approached the terminal, pedestrians would be visible at the terminal and at the parking lot across the street from the terminal. At some terminals, these pedestrians would be walking perpendicular to the street and would begin to cross the street just before the driver reached the crossing. At other terminals (the data collection terminals), one pedestrian approached the crossing location on the side nearest to the driver’s vehicle as if to cross (but did not) while the remaining terminal and parking lot pedestrians did not move.

Data collection drives lasted until 1 minute after the participant drove past a simulated bus terminal with a MSU billboard or a maximum of 10 minutes. After two drives, the participant would take a break outside of the vehicle where water and snacks were provided. During each break, the participant completed another MSSQ. The MSSQ was compared to previous MSSQ forms and the baseline to determine if a participant was showing signs of simulator sickness.

Data was collected on a specific street in each scenario. The street was divided into three zones, with zone 2 being the primary area of interest. In zone 2, drivers pass the crosswalk and the intermodal transportation terminal. Only data from zone 2 was included subsequent analyses.

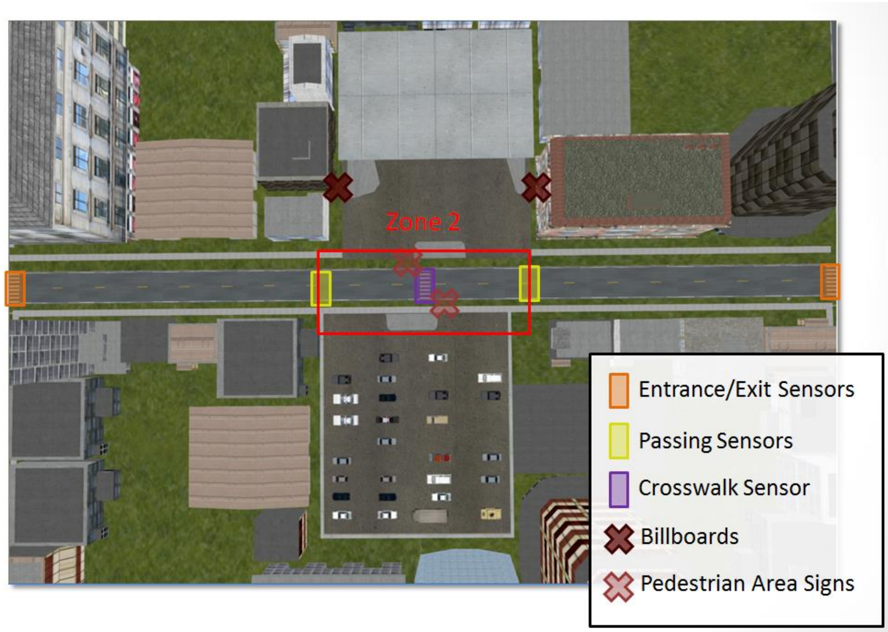

Figure 2: Data collection segments

The experiment ended either when all eight drives were completed, or when the participant or experiment requested early termination of the experiment for any reason (such as indications of simulator sickness). At this time the participant was informed of the aim of the study, given a payment of $20 cash, and signed a receipt form. The payment for each participant was a flat fee of $20, whether they were able to complete one drive or all eight.

Data Preparation and Analysis

In order to clean the raw data collected from the simulator, first, outliers were removed. Outliers included extreme values collected from some participants who displayed extreme driving maneuvers. For example, excessive speeding or cutting through turns or streets. Descriptive statistics are presented using raw data values. Inferential statistics are presented using transformed data values. A log transformation was performed on every variable to satisfy normality assumptions of subsequent analyses.

DISCUSSION OF RESULTS

Descriptive Statistics

Table 1 lists the descriptive statistics for all variables for zone 2 with outliers removed. In addition to the zone 2 analysis, the dependent variables were also analyzed for the period of time when the driver was crossing the location of the pedestrian crosswalk in the middle of zone 2. There were no significant differences between the results of the crosswalk data analysis and the overall zone 2 data analysis. A table of descriptive statistics from the crosswalk data is shown below (Table 2).

Table 1: Descriptive Statistics by Dependent Variable for Zone 2

	Mean	Standard Deviation	Min	Max
Max Velocity	24.7	4.7	14.2	41.6
Avg Velocity	21.0	6.3	8.2	38.9
SD Velocity	2.2	2.1	0.0	8.6
Max Throttle	15.0	9.9	0.6	45.1
Avg Throttle	8.0	5.8	0.1	32.6
SD Throttle	4.0	3.7	0.2	15.2
Max Brake	16.7	18.9	0.0	90.2
Avg Brake	3.5	4.7	0.0	21.5
SD Brake	5.0	6.6	0.0	32.8
Max Lane Offset	-0.3	0.2	-1.1	0.4
Avg Lane Offset	-0.5	0.3	-1.2	0.3
SD Lane Offset	0.1	0.1	0.0	0.3
Max Steering	0.1	0.1	-0.0	1.0
Avg Steering	0.0	0.0	-0.1	0.1
SD Steering	0.1	0.1	0.0	0.4

Table 2: Descriptive Statistics by Dependent Variable for Crosswalk Subsection Only

	Mean	Standard Deviation	Min	Max
Max Velocity	25.0	5.1	14.2	45.8
Avg Velocity	21.1	6.5	8.2	38.9
SD Velocity	2.2	2.1	0.0	8.6
Max Throttle	16.1	12.5	0.6	90.0
Avg Throttle	8.4	6.8	0.1	51.3
SD Throttle	4.3	4.3	0.2	29.3
Max Brake	17.6	20.6	0.0	100.2
Avg Brake	3.6	4.9	0.0	21.5
SD Brake	5.2	7.0	0.0	32.8
Max Lane Offset	-0.3	0.5	-1.1	2.7
Avg Lane Offset	-0.5	0.3	-1.2	0.3
SD Lane Offset	0.1	0.1	0.0	1.2
Max Steering	0.2	0.8	-0.0	9.5
Avg Steering	-0.0	0.3	-2.9	0.1
SD Steering	0.1	0.5	0.002	4.9

Velocity and lane offset profiles of two participants can be found in Appendix A. Participant 11 had the additional IVT warning system and participant 20 did not. Figures 12 and 13 depict the velocity profiles for participant 20 in scenario 0 (no infrastructure present) and scenario 7 (all infrastructure present). The velocity profile for participant 11 in the same two scenarios is shown in Figures 14 and 15. The lane offset profiles for participant 20 in both scenario 1 and 7 are displayed in Figures 16 and 17. Finally the lane offset profile of participant 11 is represented in Figures 18 and 19. These profiles were generated using raw data from zone 2. Figures 20 through 27 show the response curves for the crosswalk subsection only.

Inferential Statistics

ANOVAs on performance data versus infrastructure changes were performed. Table 3 summarizes the p-values from the various ANOVAs performed. The presence of the high pedestrian alarm (IVT) impacted driver average velocity and lane position. The presence/absence of sidewalks impacted driver average velocity as well as maximum braking and throttle forces. Table 4 displays the interaction effects between our variables. Three interactions were significant. These include SD Velocity, SD Throttle, and SD Lane Offset each versus sidewalk*crosswalk.

Table 3: Intervention effect on performance measures (p-value, bold indicates significance)

	IVT	Crosswalk	Sidewalk	Signal
Max Velocity	0.054	0.705	0.323	**<0.001**
Avg Velocity	**0.004**	0.386	**0.001**	**<0.001**
SD Velocity	**0.006**	0.171	**0.039**	**0.001**
Max Throttle	**0.002**	0.835	**0.002**	**0.022**
Avg Throttle	**0.002**	0.744	0.054	**0.024**
SD Throttle	**0.044**	0.981	**0.002**	**0.040**
Max Brake	0.925	0.105	**0.014**	0.537
Avg Brake	0.762	0.100	**0.035**	0.422
SD Brake	0.748	0.128	**0.011**	0.448
Max Lane Offset	**0.038**	0.077	**0.041**	0.167
Avg Lane Offset	**0.008**	**0.039**	**0.037**	0.184
SD Lane Offset	0.062	0.624	0.507	0.701
Max Steering	0.299	0.355	0.229	0.781
Avg Steering	0.574	0.571	0.669	0.511
SD Steering	0.221	0.478	0.132	0.300

Table 4: Interaction effect on performance measures (p-value, bold indicates significance)

	Crosswalk * Sidewalk	Crosswalk * Signal	Crosswalk * IVT	Sidewalk * Signal	Sidewalk * IVT	Signal * IVT
Max Velocity	0.547	0.205	0.367	0.227	0.671	0.762
Avg Velocity	0.093	0.216	0.963	0.904	0.625	0.465
SD Velocity	0.335	0.935	0.707	0.317	0.512	0.898
Max Throttle	0.111	0.612	0.733	0.563	0.888	0.389
Avg Throttle	0.071	0.463	0.571	0.832	0.947	0.955
SD Throttle	0.061	0.935	0.755	0.377	0.977	0.393
Max Brake	0.483	0.744	0.752	0.553	0.528	0.952
Avg Brake	0.872	0.726	0.935	0.596	0.650	0.787
SD Brake	0.408	0.750	0.829	0.703	0.445	0.951
Max Lane Offset	0.884	0.279	0.668	0.274	0.491	0.930
Avg Lane Offset	0.489	0.588	0.846	0.402	0.508	0.847
SD Lane Offset	**0.012**	0.157	0.377	0.258	0.836	0.846
Max Steering	0.411	0.546	0.781	0.774	0.925	0.316
Avg Steering	0.289	0.710	0.534	0.963	0.857	0.509
SD Steering	0.558	0.595	0.390	0.746	0.344	0.413

A plot of the single observed interaction effect (crosswalk*sidewalk for SD lane offset) is presented in Figure 3. This shows that the effect of presence of a crosswalk was modified by the presence of the sidewalk.

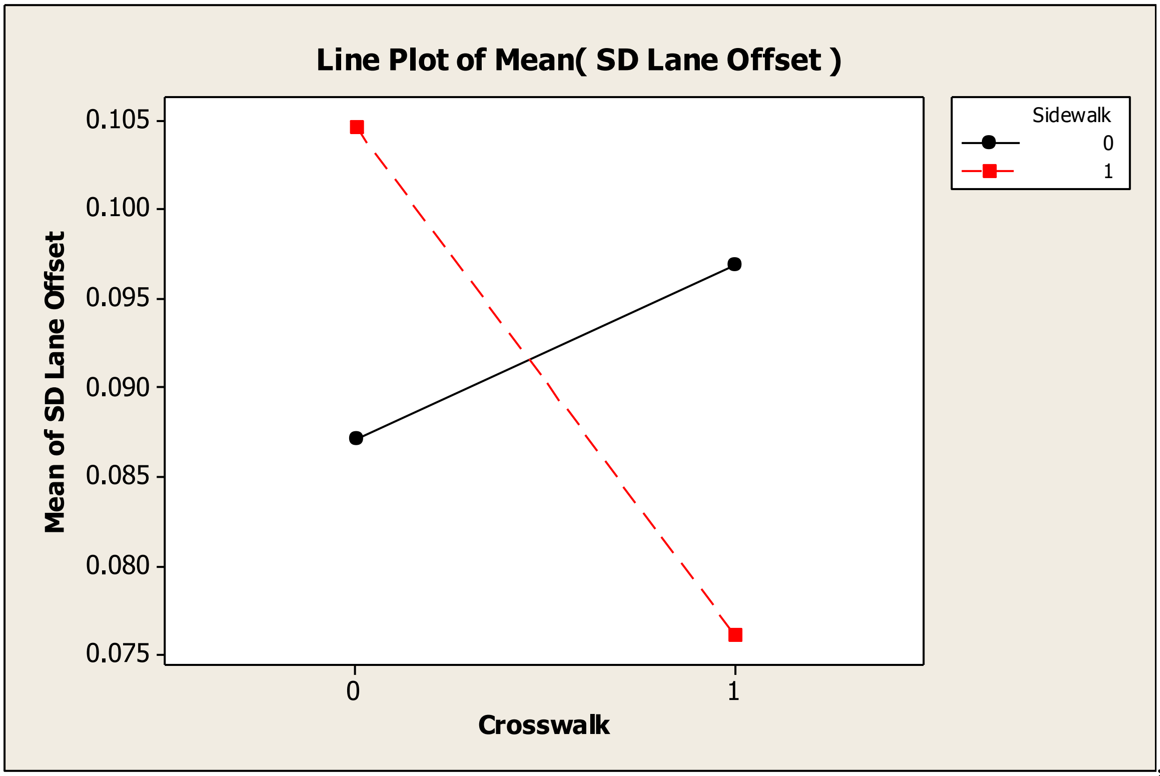

Figure 3: Plot of the interaction between the side walk and crosswalk variables

When the sidewalk is absent, pedestrians in the environment are walking along the side of the road. There is almost no separation between the road surface and the path of the pedestrians. In response, drivers shift their lane position to the left and away from the pedestrians (see Table 3 and Table 5). Variability in lane offset is between .085 and 0.1 when the sidewalk is absent regardless of the presence of the crosswalk. A possible interpretation of these results is that when the sidewalk is absent, drivers may be shifting away from pedestrians as they encounter them on the right side of the road and shifting back towards the right side of the road after they pass the pedestrians. When the sidewalk is present and the crosswalk is present, variability in the lane offset is lowest. This may be because the drivers maintain their position nearer the edge of the road because the pedestrians are a safer distance away (~3m) and the drivers do not expect the pedestrians to cross the street outside of the marked location. However, when the sidewalk is present but the crosswalk is absent, variability is highest. In this case, the drivers may be responding to pedestrians moving toward the street and veering more drastically away from the shoulder in response to the unexpected (due to no marking) perception of pedestrians about to cross the street. Within the scenario, pedestrians did not cross the street in front of the driver's vehicle. However, they did walk towards the street as if they had an intention to cross. This pedestrian behavior could have contributed to higher variability in lane position during the crosswalk absent condition.

Table 5: Average values for each performance measure by IV level. Bolded values indicate significant difference between present and absent conditions.

	IVT		Crosswalk		Sidewalk		Signal	
	Present	Absent	Present	Absent	Present	Absent	Present	Absent
Max Velocity	24.0	25.3	24.9	24.5	25.2	24.2	23.2	26.0
Avg Velocity	19.6	22.2	20.7	21.2	22.4	19.5	18.6	23.0
SD Velocity	2.6	1.8	2.4	1.9	1.7	2.6	2.6	1.8
Max Throttle	17.4	12.8	15.8	14.1	12.7	17.2	16.7	13.5
Avg Throttle	9.6	6.7	8.6	7.5	7.3	8.8	9.0	7.2
SD Throttle	3.5	3.2	4.3	3.8	3.1	5.0	4.8	3.5
Max Brake	15.7	17.5	18.8	14.4	12.3	21.0	18.5	15.1
Avg Brake	3.8	3.1	4.0	3.0	2.8	4.1	4.0	3.1
SD Brake	4.4	5.3	5.6	4.2	3.5	6.3	5.8	4.2
Max Lane Offset	-0.3	-0.4	-0.3	-0.4	-0.3	-0.4	-0.3	-0.3
Avg Lane Offset	-0.4	0.5	-0.4	-0.5	-0.4	-0.5	-0.5	-0.5
SD Lane Offset	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Max Steering	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Avg Steering	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SD Steering	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

In Vehicle Technology (IVT)

The bar graphs below provide visual descriptions of the relationship between the dependent and independent variables. The in-vehicle technology (IVT) significantly impacted the driving performance of the participants. As shown below in Figure 4, the average velocity of drivers with the IVT (M: 19.6) was significantly lower than those without the technology (M: 22.2, $p < .01$). Variance in velocity was also lower for those drives provided with the IVT (M: 1.8) than those without the IVT (M: 2.6, $p < .01$). In addition to changes in velocity, use of the throttle was higher for those with the IVT (Max: 17.4, M: 9.6, SD: 6.7) as compared to those without the IVT (Max: 12.8, M: 6.7, SD: 3.5, $p < .01$). The lane offset of those drivers provided with the IVT (Max: -0.36, M: -0.53) was positioned significantly further to the right, toward the sidewalk, than those driving without it (Max: -0.28, M: -0.42, $p < .05$; see Figure 5). There were no differences in steering or in use of the brake between the two IVT conditions.

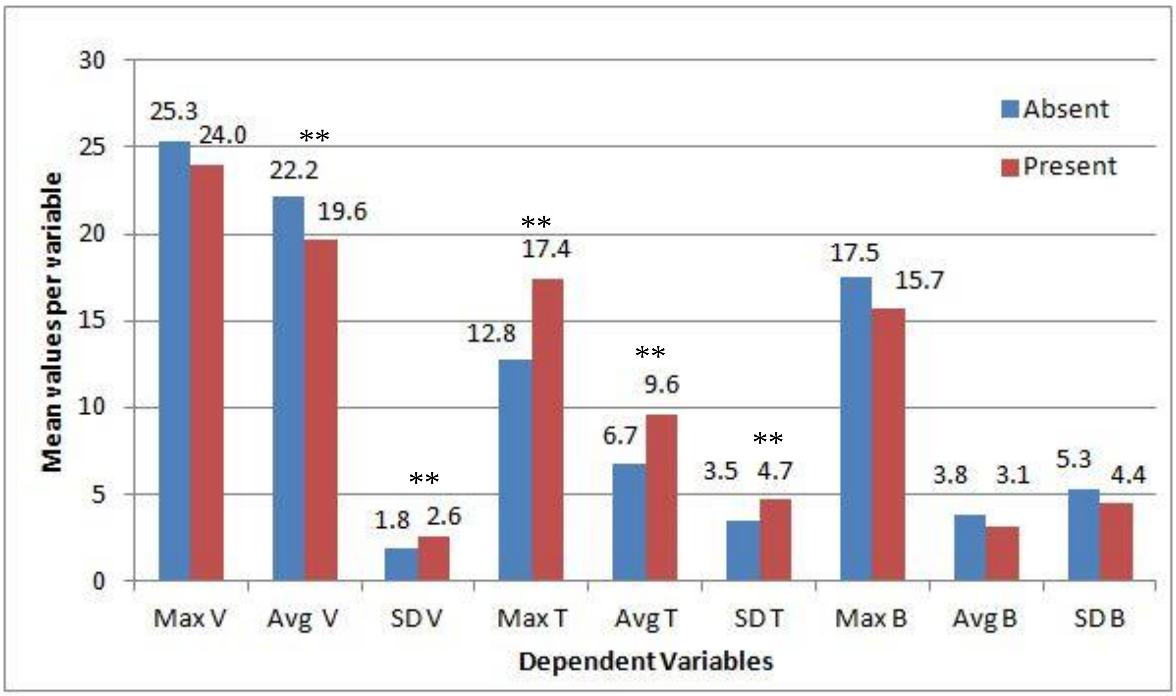

Figure 4: Bar graph for speed parameters (mph) - assessing impact of IVT. Dependent variables include velocity (V), throttle (T), and brake (B).

Figure 5: Bar graph for position parameters (deviation from center; 0) – assessing impact of IVT. Dependent variables include lane offset (LO) and steering (S).

Crosswalk

The impacts of crosswalks can be seen in Figures 6 and 7. We observed significant differences in driver behavior for only one dependent variable: average lane offset. Drivers were positioned closer to the right edge of the road, closer to pedestrians, when crosswalks were present (M: -0.43) as compared to when crosswalks were absent (M: -0.52, $p < .05$). This is surprising as there is no obvious connection between presence of crosswalks and lane position. A possible explanation is that when crosswalks are present, drivers assume pedestrians will cross at the crosswalk and feel more comfortable driving closer to the right side of the road. As previously described, the impact of crosswalks does interact with the impact of sidewalks. There were no significant differences in velocity, use of the throttle, use of the brake, or steering.

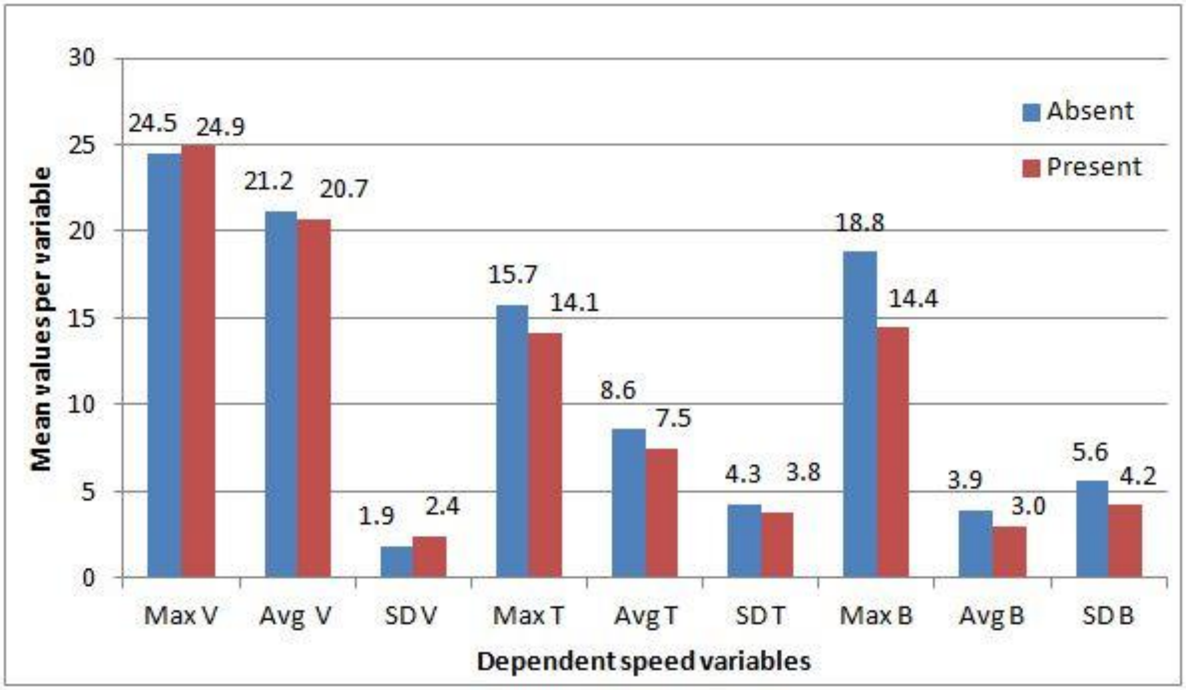

Figure 6: Bar graph for speed parameters (mph) – assessing impact of crosswalks. Dependent variables include velocity (V), throttle (T), and brake (B).

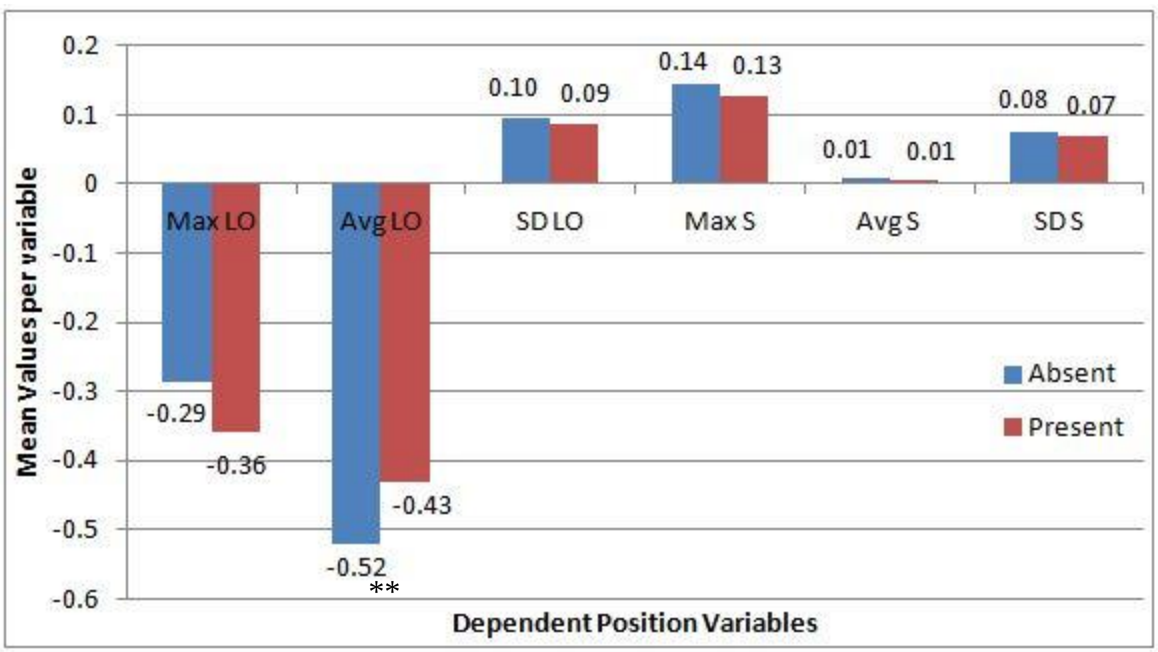

Figure 7: Bar graph for position parameters (deviation from center; 0) - assessing impact of crosswalks. Dependent variables include lane offset (LO) and steering (S).

Sidewalk

In Figures 8 and 9 below the impact of sidewalks on driver behavior is shown. We observed a significant impact of sidewalks on driver behavior on most of the dependent variables. Driver average velocity was higher when sidewalks were present (M: 22.4) than when sidewalks were absent (M: 19.5, $p < .01$). However, variability in velocity was lower when sidewalks were present (SD: 1.7 vs SD: 2.6, $p < .05$). In addition to lower variability in velocity, use of the throttle and brakes were lower when the sidewalk was present (Max_T: 12.7, SD_T: 3.1, Max_B: 12.3, M_B: 2.8, SD_B: 3.5) compared to when the sidewalk was absent (Max_T: 17.2, SD_T: 5.0, Max_B: 20.9, M_B: 4.1, SD_B: 6.3, $p < .05$). As expected, driver lane position was closer to the right side of the road when sidewalks were present (Max: -0.28, M: -0.43) than when sidewalks were absent (Max: -0.36, M: -0.52, $p < .05$). There were no significant differences in steering.

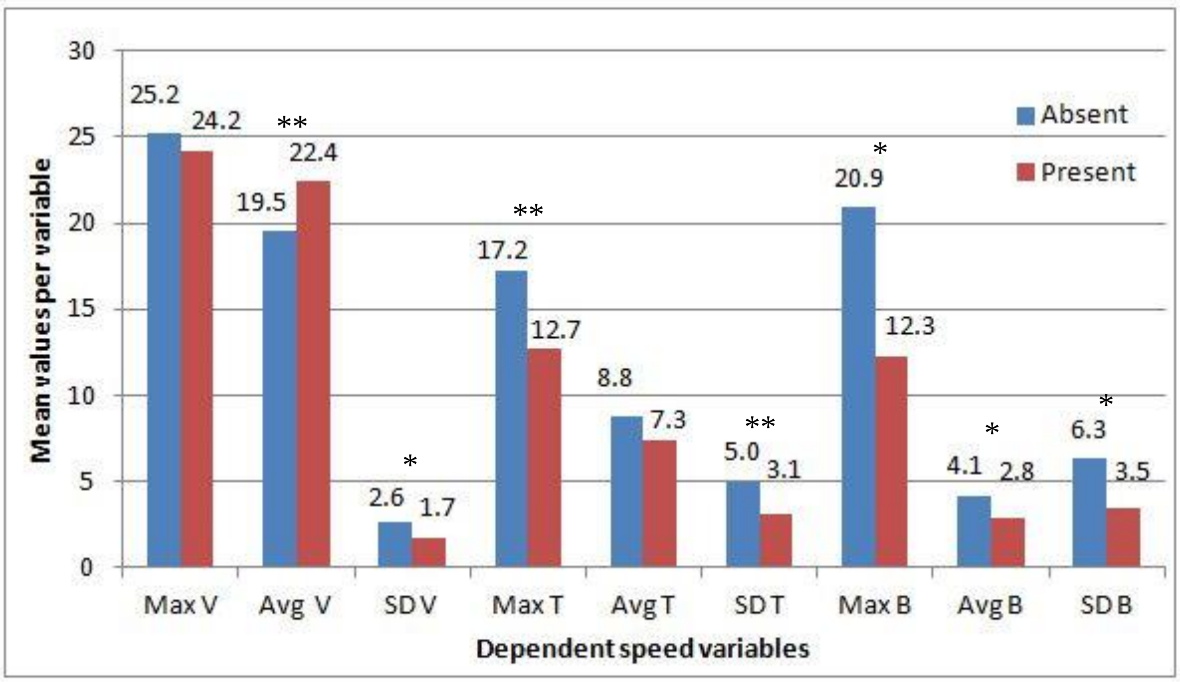

Figure 8: Bar graph for position parameters (mph) – assessing impact of sidewalks. Dependent variables include velocity (V), throttle (T), and brake (B).

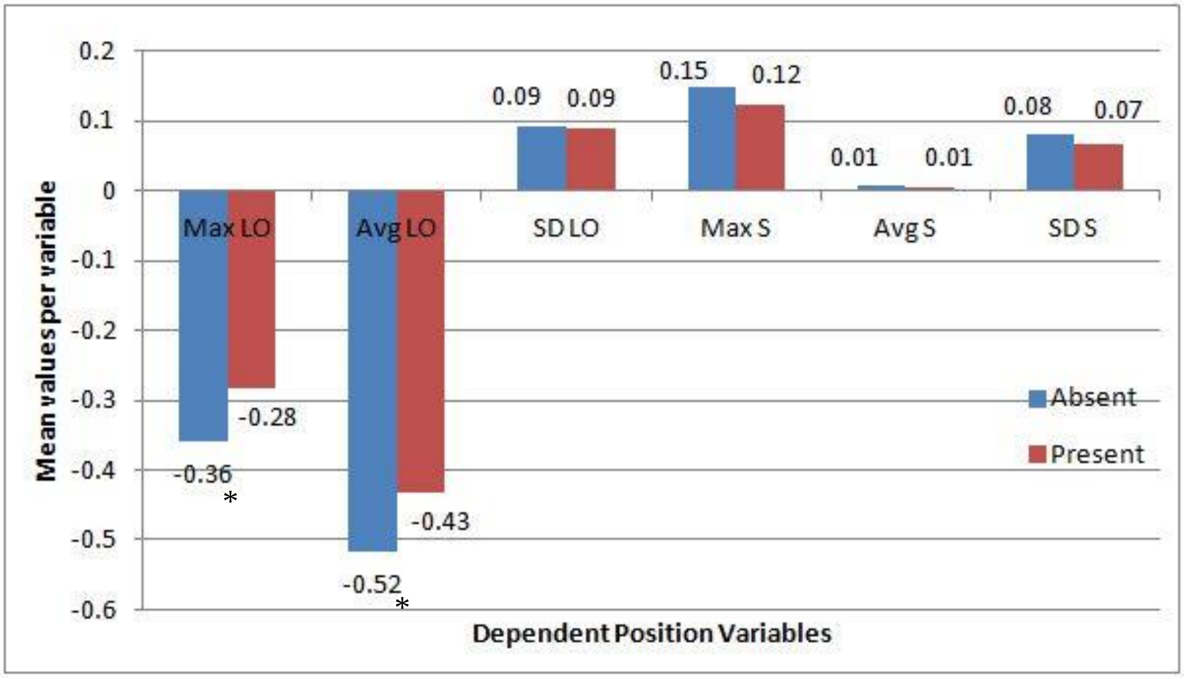

Figure 9: Bar graph for position parameters (deviation from center; 0) – assessing impact of sidewalks. Dependent variables include lane offset (LO) and steering (S).

Signal

The presence of pedestrian crossing signals significantly impacted all of the velocity and throttle dependent variables. We observed reduced maximum and average velocity when signals were present (Max: 23.2, M: 18.6) compared to when signals were absent (Max: 26.0, M: 23.2, $p < .001$). Variability in velocity was higher when signals were present (SD: 2.6) than when signals were absent (SD: 1.8, $p < .01$). Drivers also exhibited higher maximum throttle and higher variability in throttle position the crossing signals were present (Max: 16.7, SD: 4.7) as compared to when signals were absent (Max: 13.5, SD: 3.5, $p < .05$). However, average throttle was higher for the present condition (M: 9.0) than the absent condition (M: 7.2, $p < .05$). There were no significant differences in use of brake, lane offset, or steering.

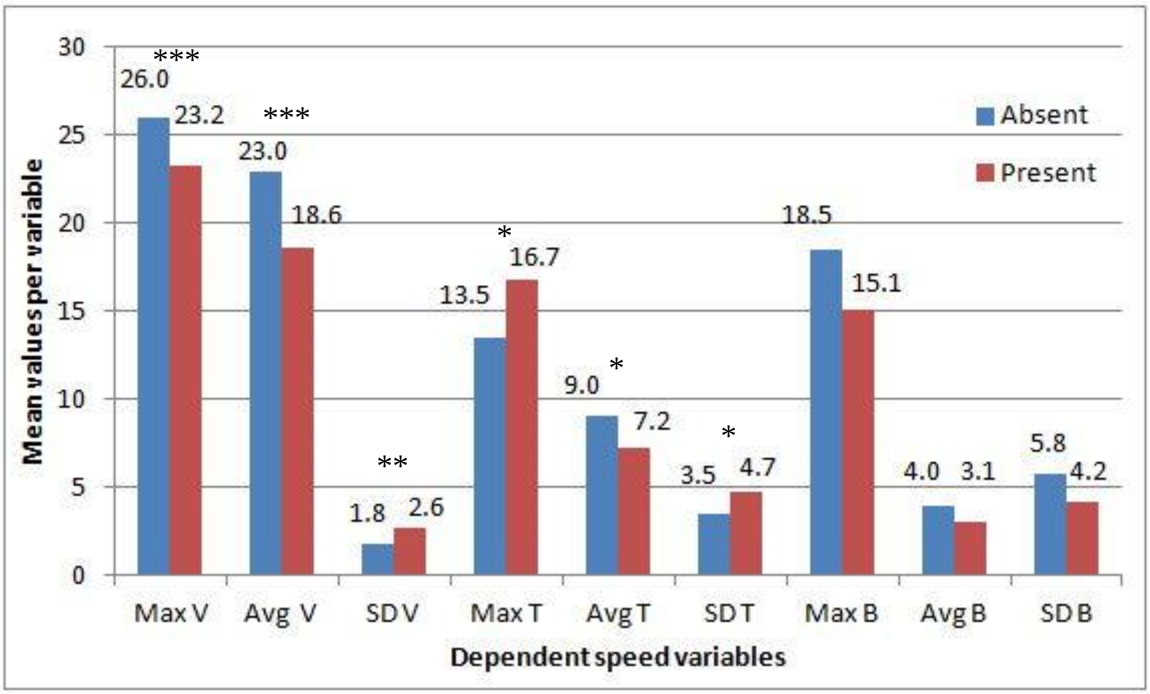

Figure 10: Bar graph for position parameters (mph) – assessing impact of signals. Dependent variables include velocity (V), throttle (T), and brake (B).

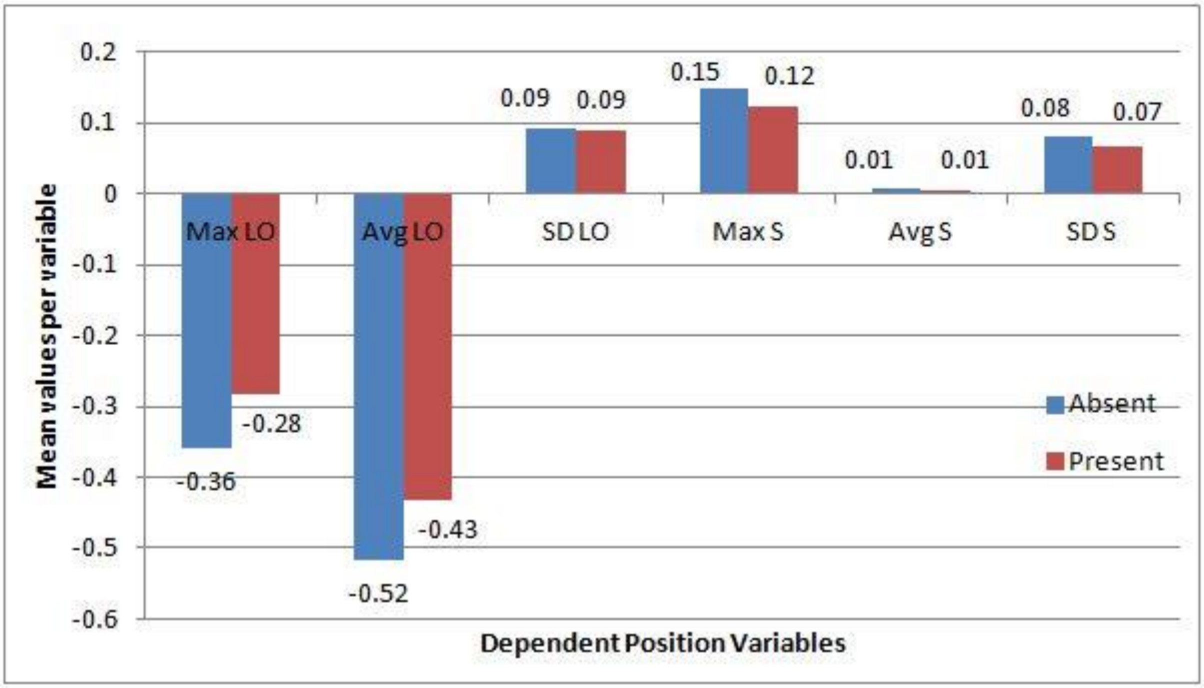

Figure 11: graph for position parameters (deviation from center; 0) – assessing impact of signals. Dependent variables include lane offset (LO) and steering (S).

CONCLUSIONS

This study provides insight into how proposed in-vehicle technologies and common infrastructure impact driver behavior. The in-vehicle technology used in the study consisted of a simple intervention: repetition of a single tone three times and coinciding with activation of an in-dash light when entering and exiting a "high pedestrian area." Drivers with the IVT were slower as they passed by our high pedestrian bus terminal and parking lot but they were closer to the pedestrians located on the side of the road. While the reduced speed of the vehicle is likely to improve pedestrian safety, particularly for those crossing the street, the shift closer to pedestrians on the side of the road puts those pedestrians at risk. An additional consideration for the IVT is that IVT alarms such as the one implemented in the study are not in use in vehicles on the road today and the effect of the system may be reduced as drivers accommodate to the presence of the alarm.

This study investigated three interventions to improve pedestrian safety: crosswalks, sidewalks, and pedestrian crossing signals posted where pedestrians can cross the street. Surprisingly, crosswalks had little impact on observed driver behavior and the one behavior that was changed appears to have little relevance to crosswalks. When crosswalks were present, driver average lane position was shifted to the right, toward the pedestrians on the side of the road. When sidewalks were not present (and pedestrians were walking on the edge of the road), lane position variability was higher which suggests that the drivers may have moved away from the shoulder as they approached pedestrians and back toward the shoulder after passing them. When sidewalks and crosswalks were present, lane offset variability was lowest which may suggest that crosswalks did provide drivers with some warning that pedestrians may cross at the location. The primary benefit of crosswalks may be to pedestrians rather than drivers.

In the study environment, sidewalks provide protection for pedestrians by providing a grassy separation between the road surface and a clearly marked footpath. This creates space between pedestrians and vehicles. We observed clear changes in driver behavior across all of the dependent variables except steering. However, the observed driver behavior (higher average speed and less variability in speed and controls) suggests that drivers were engaging in risk compensation. With additional space, drivers choose to maintain a higher speed while passing through zone 2 and exhibit less variability suggesting that they do not slow as they approach the crossing and do not accelerate after passing.

The pedestrian crossing signals used in this study provide a clear indication to drivers that they are approaching a location at which pedestrians can be expected to cross the road. When pedestrian crossing signals were present, we observed lower vehicle velocity suggesting that the signals lead to the desired driver behavior.

In summary, the IVT alarm and pedestrian crossing signals effectively reduced driver velocity in our "high pedestrian area." However, the IVT alarm may benefit from a novelty effect and also led to drivers driving closer to the shoulder and pedestrians. Sidewalks physically separate drivers and pedestrians, but we observed risk compensation behaviors in our drivers. Crosswalks had little impact on driver behavior.

RECOMMENDATIONS

Pedestrian signs appear to effectively increase safety for pedestrians crossing the street. As drivers respond to presence of sidewalks with risk compensation behaviors (faster speeds and closer to the shoulder), a separation between the sidewalk and the roadway is recommended. Crosswalks by themselves appear to have little effect on driver behavior but, particularly when combined with pedestrian crossing signs, indicate to pedestrians where it may be safer to cross. We recommend the placement of signed crosswalks mid-street where there is high pedestrian traffic.

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APPENDIX A

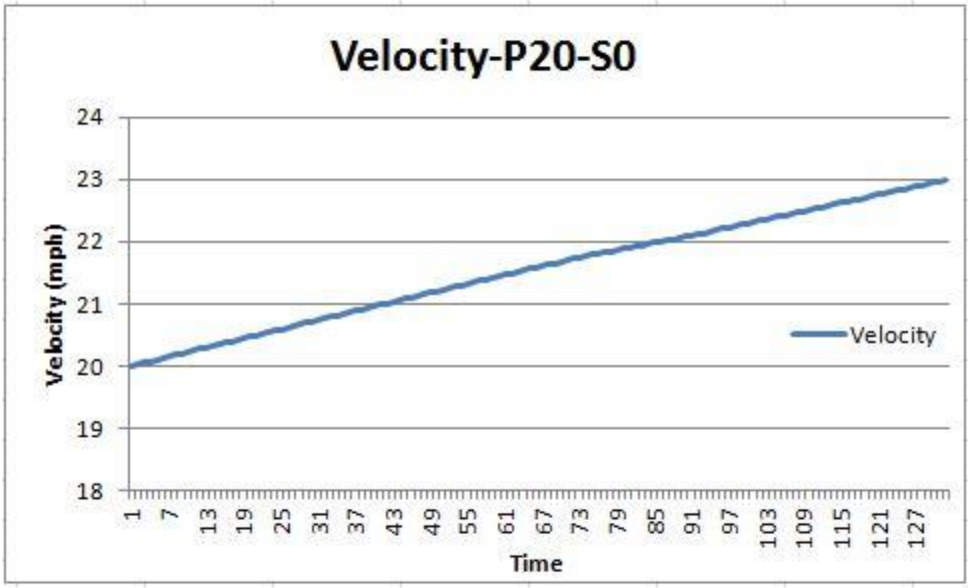

Figure 12: Velocity profile of participant 20 in scenario 0

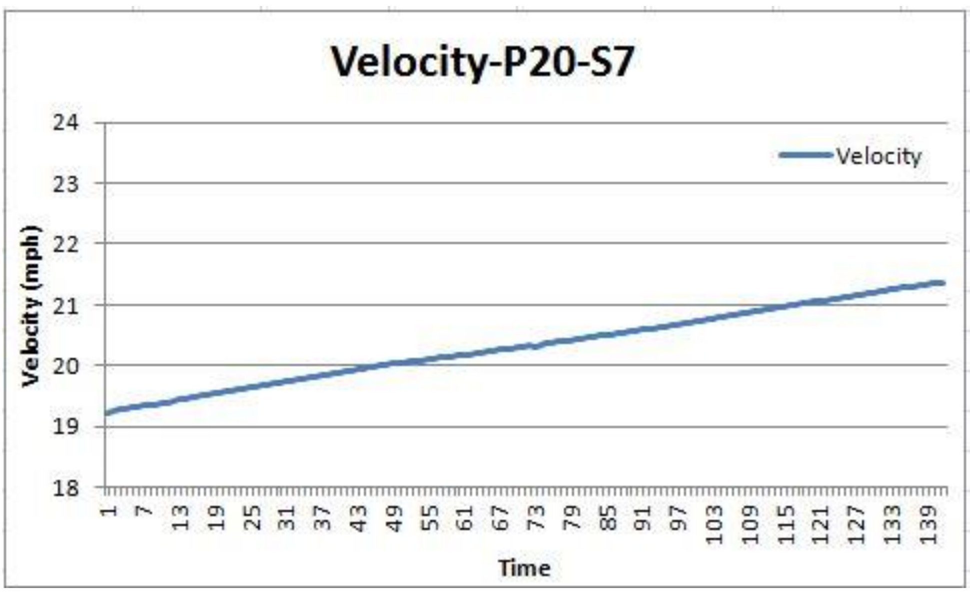

Figure 13: Velocity profile of participant 20 in scenario 7

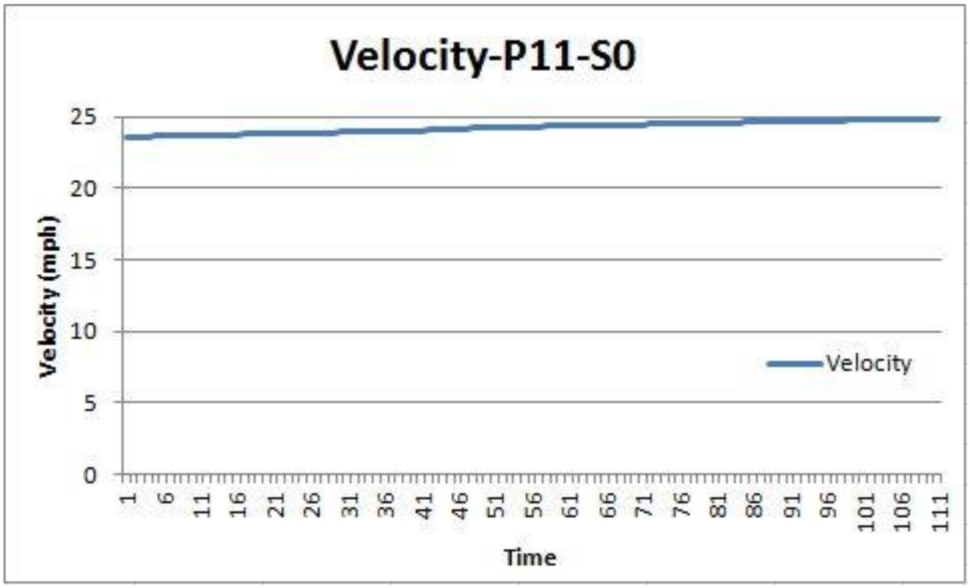

Figure 14: Velocity profile of participant 11 in scenario 0

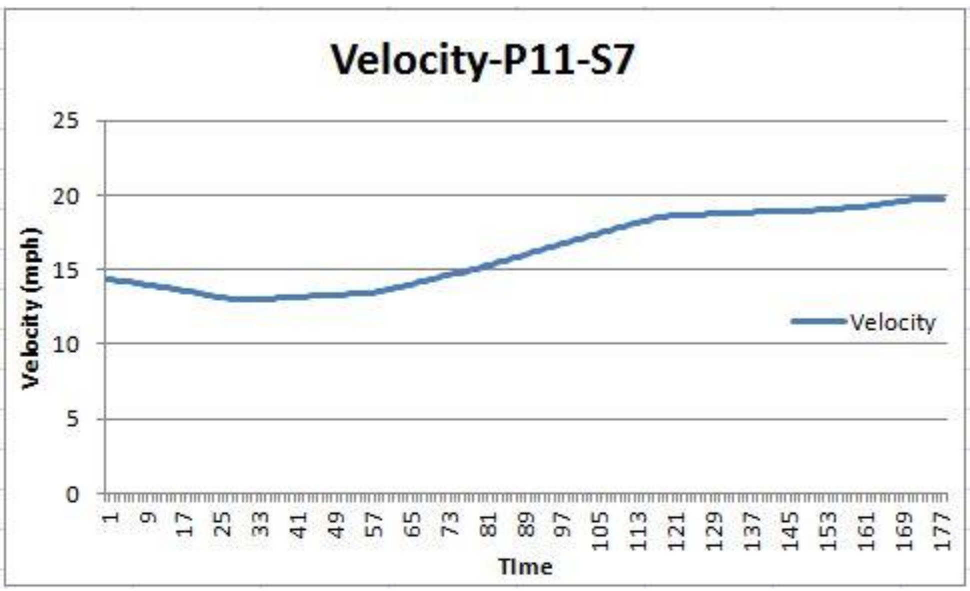

Figure 15: Velocity profile of participant 11 in scenario 7

Figure 16: Lane offset profile of participant 20 in scenario 0

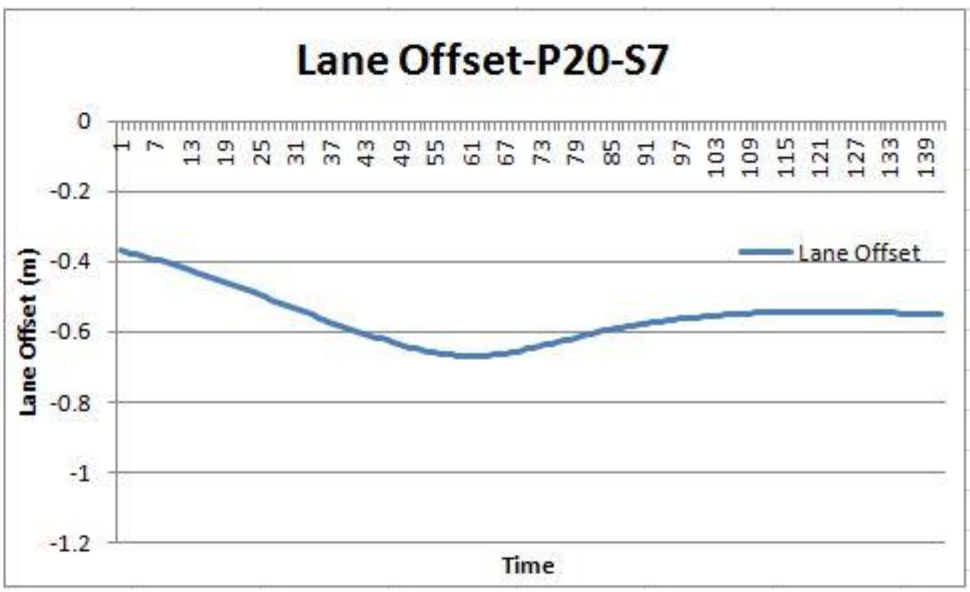

Figure 17: Lane offset profile of participant 20 in scenario 7

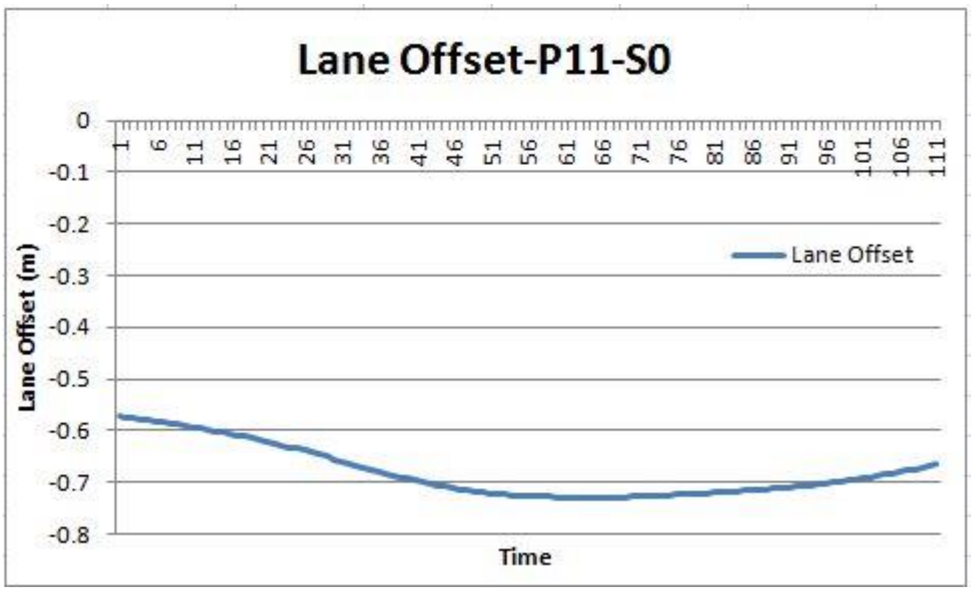

Figure 18: Velocity profile of participant 11 in scenario 0

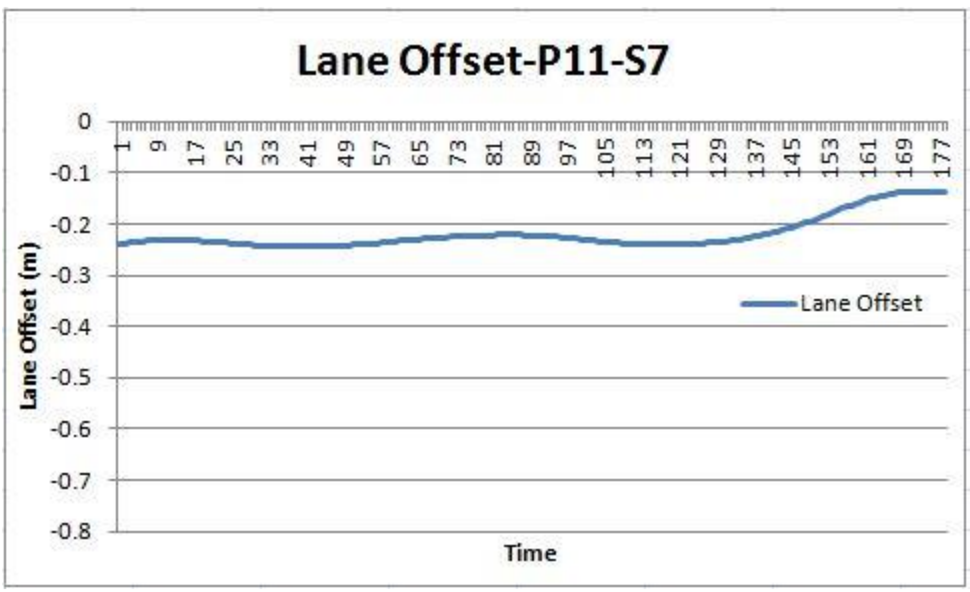

Figure 19: Lane offset profile of participant 11 in scenario 7

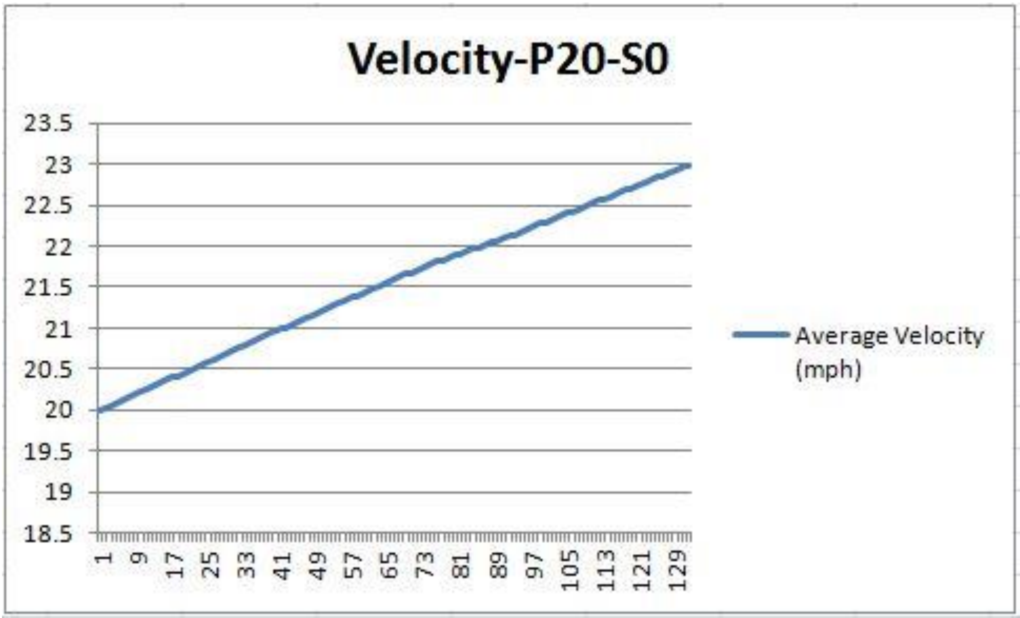

Figure 20: Velocity profile for crosswalk section for participant 20 in scenario 0

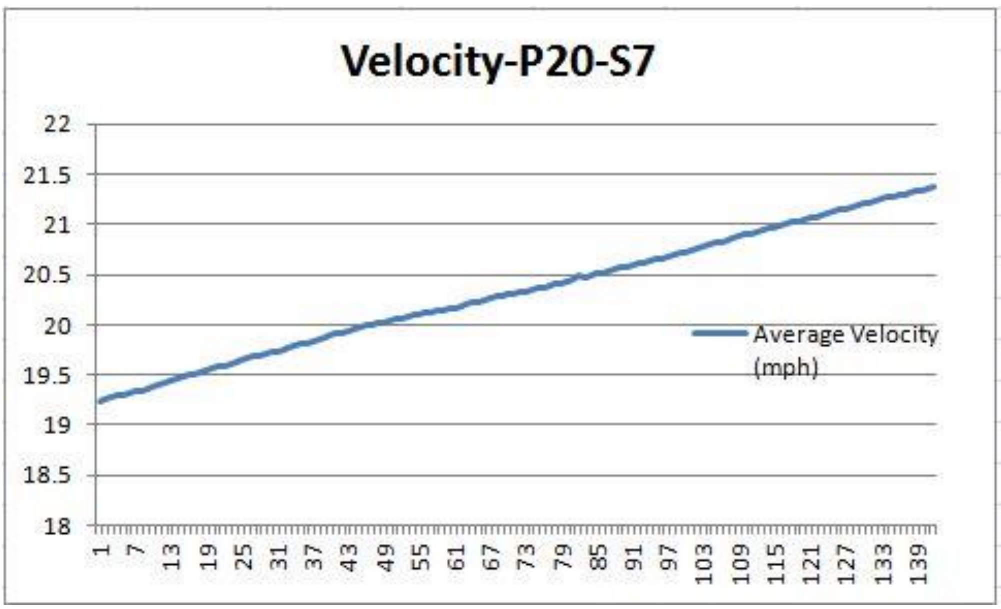

Figure 21: Velocity profile for crosswalk section for participant 20 in scenario 7

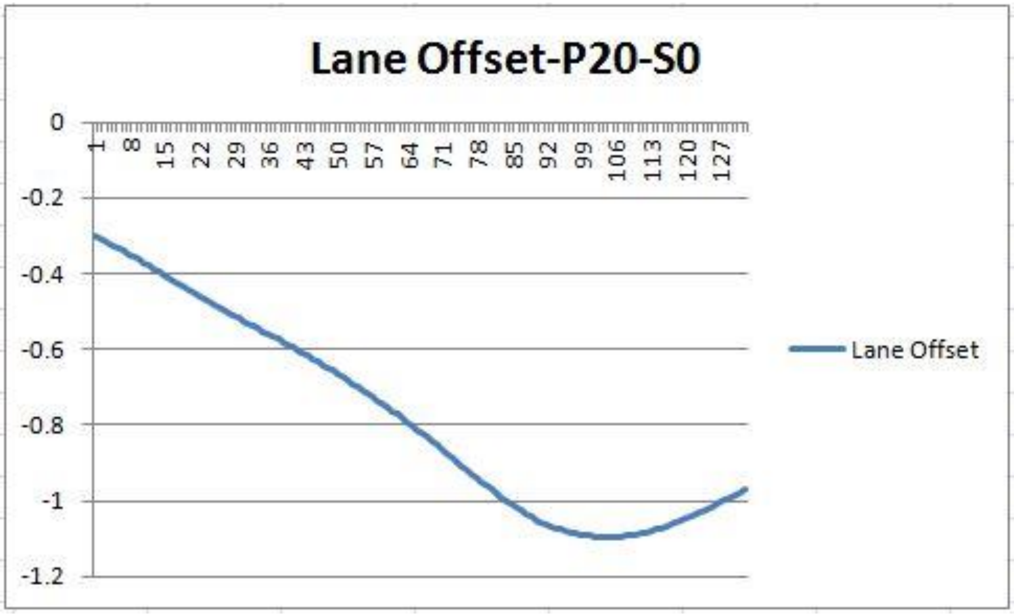

Figure 22: Lane offset profile for crosswalk section for participant 20 in scenario 0

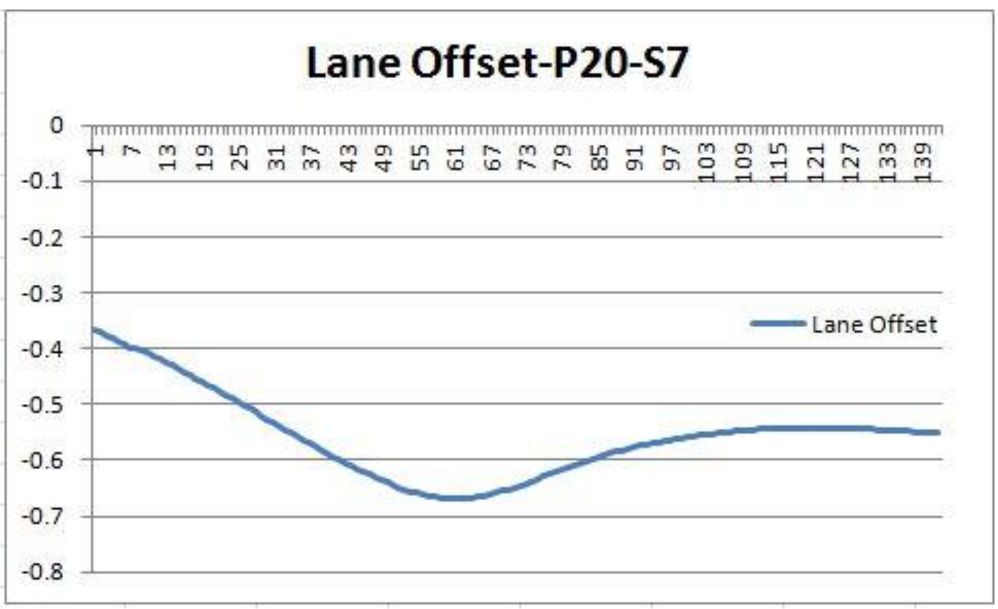

Figure 23: Lane offset profile for crosswalk section for participant 20 in scenario 7

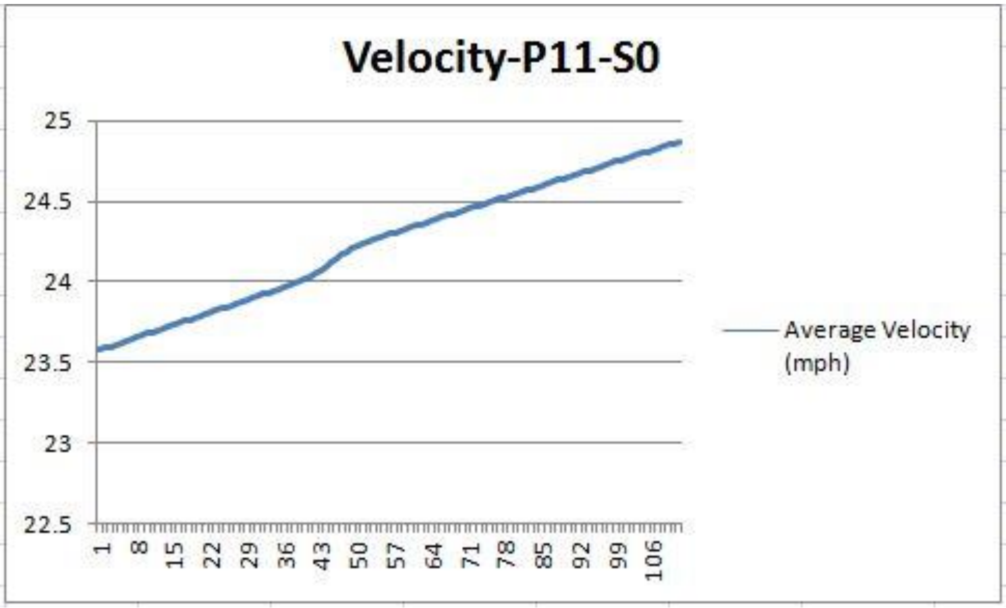

Figure 24: Velocity profile through crosswalk section for participant 11 in scenario 0

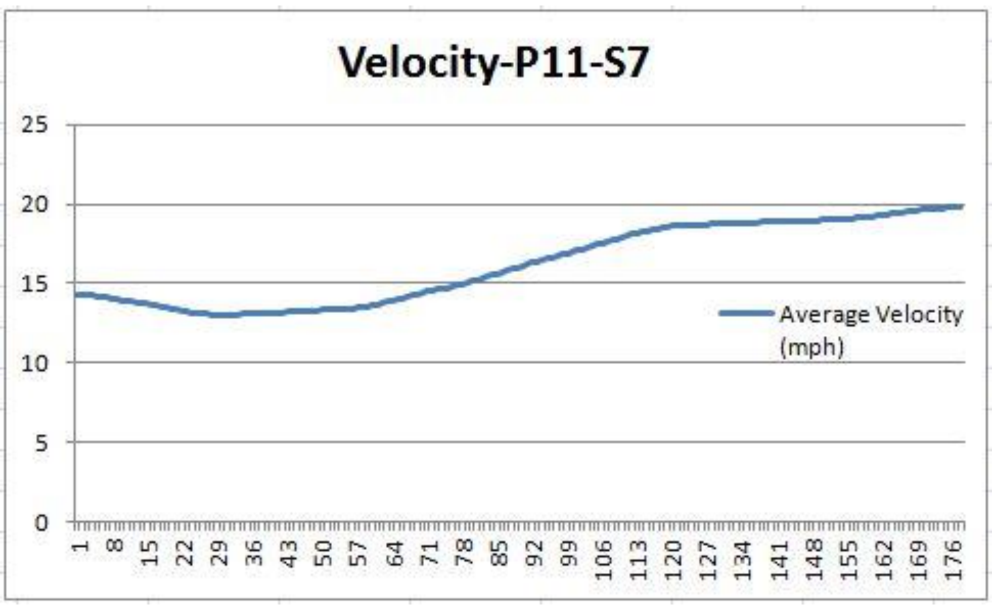

Figure 25: Velocity profile through crosswalk section for participant 1 in scenario 7

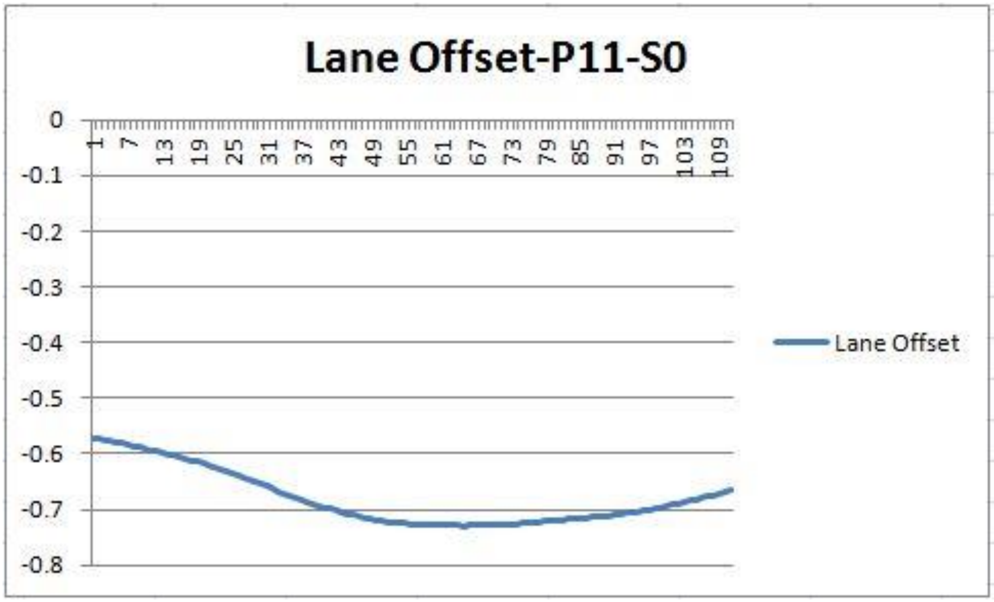

Figure 26: Lane offset profile for crosswalk section for participant 11 in scenario 0

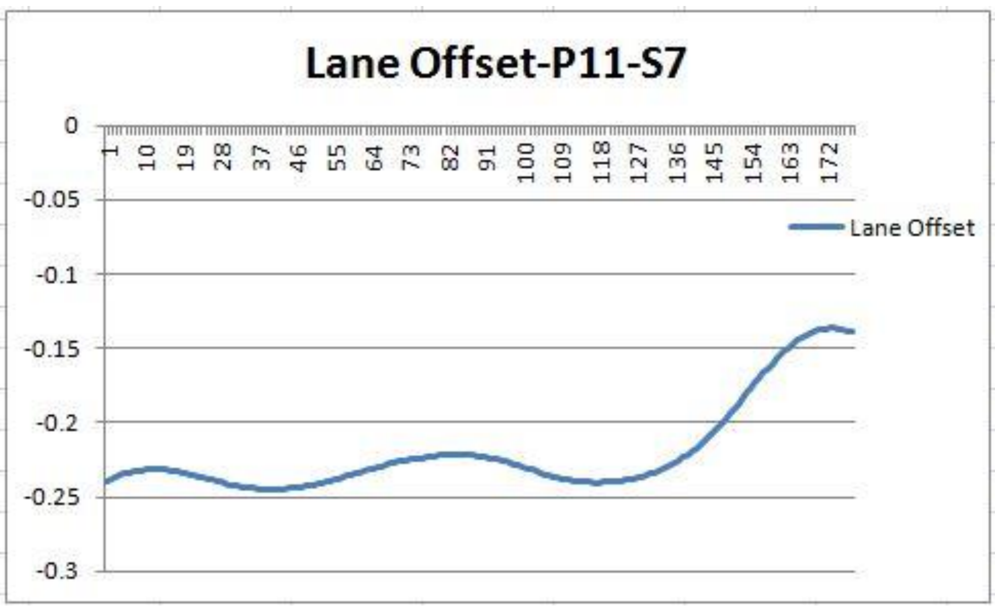

Figure 27: Lane offset profile for crosswalk section for participant 11 in scenario 7