Analysis of Walking Speeds and Success Rates on Mid-Block Crossings using Virtual Reality Simulation

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1. Introduction

Uncontrolled mid-block crossings present a potentially hazardous road scenario as pedestrians must analyze the speeds and gaps available in the traffic stream to perform the crossing maneuver in a safe manner without the assistance of traffic signals or stop signs. Yannis (2010) stated that the pedestrian gap acceptance depends on the longitudinal distance from the vehicle to the crosswalk, the pedestrian gender, the vehicle length, and the presence of illegally parked vehicles. Kadali and Vedagiri (2013) concluded the pedestrian gap acceptance depends on the pedestrian speed and age, the vehicle speed, the walking direction, and the rolling gap. Their study found that at higher vehicle speeds, pedestrians tend to make riskier crossing decisions and accept smaller gaps. When a pedestrian need to cross more than one traffic lane, there might not be a proper gap and the pedestrians' behavioral pattern approaches the use of a rolling gap (Boroujerdian and Nemati, 2016).

This summary presents the main results from a Virtual Reality (VR) simulation experiment that studied the gap acceptance decision and walking speeds of pedestrians when crossing an urban street at a mid-block location. VR simulation provides the subject with a role-playing situation with almost complete sensory immersion (sight and hearing) with scenarios that allow the control of the parameters under investigation (Schwebel et al., 2008; de Winter et al., 2012). VR can confront pedestrians with simulated complex roadway situations, enabling researchers to study human behavior and performance for road safety issues that in real life could be dangerous or non-replicable and allows the evaluation of new road design features and traffic control devices.

2. Description of the Experimental Scenarios

A VR experiment was used to analyze crossings maneuvers in a one-lane and a two-lane street configuration in a city context. The Unity® 2018.3.14f1 software was used to create the simulated environment and the HTC VIVE VR Pro Eye headset, with a detection zone of 32.8 ft x 32.8 ft (10 m x 10 m), was used for the simulation runs. The experiment was conducted in an empty classroom that allowed subjects to walk freely in the detection zone.

The VR scenario consisted of an 885.8 ft (270 m) tangent segment of an urban street as shown in Figure 1. A one-lane and a two-lane cross-section were used. The street cross-sections included 10-ft (3-m) wide lanes and 6-ft (1.8-m) wide sidewalks. The crossing was located at approximately the mid-point of the segment. The vehicle speed and the gap between vehicles were treated as independent variables in the experiment, as shown in Table 1. The one-lane street configuration had six scenarios with three vehicle gaps and two vehicle speeds. Two of the scenarios had vehicles generated randomly using variable 2-to-5 s gap values. The other four scenarios had fixed constant 3-s or 5-s gaps between vehicles. The two-lane street configuration included two scenarios with vehicles generated randomly and independently for each lane with variable gaps from 2 to 8 s. The speed of the vehicles was set at either 15 mph (24.1 km/h) or 25 mph (40.2 km/h) on both configurations.

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Figure 1: Scenario of the Two-Lane Street Segment.

Forty-eight subjects, from 20 to 74 years old, divided into three groups and four age groups were recruited. Thirty-two subjects were assigned to the one-lane street configuration. One group observed scenarios 1-3 and the second group observed scenarios 4-6. Each subject repeated each scenario four times in random order for a total of 12 simulation runs. The third group observed scenarios 7-8 from the two-lane street configuration. The subjects on this configuration repeated each scenario five times in random order for a total of 10 simulation runs.

Table 1: Scenarios for the One-lane and Two-lane Street Configurations

One-Lane Street Configuration					
Scenario	**Gaps (s)**	**Traffic Speed (mph)**	**Scenario**	**Gaps (s)**	**Traffic Speed (mph)**
1	2 to 5	15	4	2 to 5	25
2	3		5	3	
3	5		6	5	
Two-Lane Street Configuration					
7	2 to 8	15	8	2 to 8	25

3. Analysis of Results

The dataset of observations included 380 one-lane street crossings and 158 two-lane street crossings. The analysis of the gap acceptance and the walking speed included crossing maneuvers that were completed without the subject getting hit by a vehicle. The crossing success rate, calculated as the number of safe crossing maneuvers divided by the total crossing maneuvers, was 96.8% overall. There were 16 observations (4.2%) for the one-lane street and one observation (0.6%) for the two-lane street that resulted in subjects being hit by a vehicle.

Gap Acceptance Analysis

The number of gaps that each subject watched before making the decision to cross and the gap accepted (or selected) to cross, in seconds, was recorded for each subject. The average gap accepted was about 4.5 s with an average number of gaps seen of about 5 gaps by the subjects in the experiment. A Kruskal-Wallis test, which is a non-parametric approach to the one-way ANOVA, was used to determine if there were significant differences between the median values of the distributions of the gap accepted value and the levels of the independent variables.

The *age* was defined as a categorical variable with four levels, taking a value of zero for the 18-25 years old group, a value of one for the 26-45 age group, a value of two for the 46-65 age group, and a value of three for the 66-85 age group. The *gender* variable had a value of zero for females and one for males. The *vehicle speed* variable had a value of zero for the 15-mph speed and one for the 25-mph speed. The *number of lanes* variable had a value of zero for the one-lane street and one for the two-lane street. The *gap fixed* variable had a value of zero for the scenarios with variable gap values and a value of one for the scenarios with 3-s and 5-s fixed gap values.

The Kruskal-Wallis test results corroborate that the *age* and *gender* variables do not have significant effects on the median values of the gap accepted. In contrast, the *vehicle speed*, the *number of lanes*, and the *gap fixed* variables have a significant effect on the median values of the gap accepted with p-values lower than 0.05.

Two OLS regression models were developed to explain the effects on the average gap accepted based on subject and scenario characteristics. Table 2 shows the model results with the coefficients of the parameters with the p-values in parentheses. The base model shows the effects on the gap accepted from six independent variables. The second model added an interaction term based on the *gender* and the *number of lanes* variables, increasing the variance of the response variable explained.

Table 2: OLS Model Coefficients of the Gap Accepted

Parameter	Level	Base Model	Model w/Interaction
Constant		3.78 (<0.001*)	3.89 (<0.001*)
Age	26-45 years old	0.04 (0.77)	0.04 (0.77)
	46-65 years old	0.09 (0.54)	0.08 (0.55)
	66-85 years old	0.19 (0.21)	0.19 (0.21)
Gender	Male	0.002 (0.93)	-0.15 (0.21)
Vehicle speed	25-mph	-0.30 (<0.001*)	-0.30 (<0.001*)
Number of lanes	2-lane	1.92 (<0.001*)	1.66 (<0.001*)
Gap fixed	3-s and 5-s gaps	0.59 (<0.001*)	0.59 (<0.001*)
Gap seen	Continuous	-0.19 (<0.001*)	-0.01 (<0.001*)
Gender – Number of lanes	Male + 2-lane	---	0.53 (0.02) *
R^2		30.8%	34.8%
Adjusted R^2		29.7%	33.1%

*Note: * indicates the parameter has a significant effect on the response variable.*

The calibration of the base model includes four significant variables. The four parameters related to the scenario characteristics were found significant whereas the *age* and *gender* variables were not significant in explaining the variability in the data. The second OLS model with the interaction term improves by 11% the variability explained as indicated by the adjusted R^2 value of 33.1%. The results from both OLS models confirm that subjects on the 2-lane street and on the scenarios with a fixed gap between vehicles selected larger gaps to cross. In contrast, subjects accepted smaller gaps between vehicles in the scenarios with 25-mph. As evidence of the potential intolerance to wait of the subjects, the models indicate that the gap accepted tended to be smaller as the number of gaps seen by the subjects increased in the experiment. The *gender-number of lanes* interaction term indicates that males in the 2-lane street scenarios tended to select higher gaps to cross than their counterparts.

Walking Speed

The walking speed of the subjects was calculated by registering their actual position when crossing the street during each VR simulation runs. The distance traveled between the two sidewalks was divided by the time each subject took to cross the street. A Kruskal-Wallis test indicate there is a statistically significant difference between the median values of the walking speed for the *age* and *gender*, the *number of lanes*, and the *gap fixed* variables. In contrast to the gap accepted, the *vehicle speed* in the simulation does not significantly influence the median walking speed.

A logarithmic transformation of the average walking speed was made to stabilize the normality and variance of the residuals of the model. Three OLS regression models were developed with the logarithmic transformation over the response variable. Table 3 shows the calibration results for the OLS models with the parameter coefficients and the p-values in parentheses. A p-value of 0.10 was used as threshold to establish the statistical significance of a parameter.

The base OLS model evaluated the effect from the independent variables *age* and *gender*, *number of lanes*, *vehicle speed*, *gap accepted*, and *gap fixed*. The *age* was the only variable found to be statistically significant in explaining the walking speed. When compared with the base age condition (18-25 years old), the subjects from the 26-45 and the 66-85 years old exhibited lower walking speeds in the simulation. In contrast, subjects in the 46-65 years old exhibited higher walking speeds than their counterparts in the base age level. An alternate OLS model was calibrated by removing the *vehicle speed* and the *gap fixed* variables. Doing so, the effect of the *number of lanes* variable become significant in the model, explaining that subjects in the 2-lane street tend to use a slower walking speed when crossing. The OLS models resulted in adjusted R^2 values of 10.9% and 10.8% respectively, indicating that the two models provide similar results in terms of explaining the variability of the response variable.

A third OLS model including the effects of interactions between explanatory variables was calibrated. The linear model fit has an adjusted R^2 value of 27.9%, which is considerably better than the two OLS models without iterations. In this model, various levels from four independent variables and four interaction terms were found to be statistically significant. The *age* and *gender*, the *number of lanes*, and the *gap fixed* variables resulted significant. The *age* variable had a similar effect on the walking speed as the previous OLS models for only the subjects on the 26-45 and the 66-85 years old groups. The middle age group was deemed non-significant. The effect of *gender* is also significant, noting that males had higher walking speeds than females. In terms of the scenario characteristics, the negative effect of the higher vehicle speed of 25-mph remained significant in this model. The other characteristic found significant was the *fixed gap* variable. This effect can be interpreted as subjects on scenarios with fixed gap values, all on the one-lane street, had higher walking speeds than the subjects in scenarios with vehicles with random gap values. Several levels of the interactions between *age* and *gender*, the *number of lanes*, and the *vehicle speed* were found significant. It can be observed from the coefficient for the interaction term for the 46-65 years old from the *age* variable and the male category that it had the greatest absolute negative impact on the average walking speed. By calculating e^x, with the x representing the coefficient value obtained from the model for any parameter, an estimate of the reduction or increase in walking speed can be estimated. Males in the 46-65 years old group had the greatest overall impact with a reduction in walking speed up to 0.77 ft/s (0.23 m/s) when compared to their counterparts. In contrast, subjects in the 46-65 and 66-85 age groups, when observing the two-lane scenarios, exhibited higher walking speeds. When faced with 25-mph vehicle speeds, males tend to select lower speed than their counterparts in other scenarios. The inclusion of the interaction terms in the OLS regression model improves at least 2.5 times the capacity of explaining the variability of the response variable by identifying the combined effects of pairs of explanatory variables.

Table 3: OLS Models of the Logarithmic Transformation of the Walking Speed

Parameter	**Level**	**Base Model**	**Alternate Model**	**Interaction Model**
Constant		1.50 (<0.001*)	1.50 (<0.001*)	1.48 (<0.001*)
Age	26-45 years old	-0.09 (<0.001*)	-0.09 (<0.001*)	-0.07 (0.08*)
	46-65 years old	0.04 (0.06*)	0.04 (0.06*)	0.06 (0.13)
	66-85 years old	-0.11 (<0.001*)	-0.11 (<0.001*)	-0.11 (<0.001*)
Gender	Male	0.02 (0.16)	0.02 (0.16)	0.10 (<0.001*)
Vehicle speed	25-mph	0.003 (0.84)	--	0.03 (0.35)
Number of lanes	2-lane	-0.02 (0.54)	-0.05 (<0.001*)	-0.07 (0.06*)
Gap accepted	Continuous	-0.01 (0.20)	-0.007 (0.31)	-0.01 (0.19)
Gap fixed	3-s or 5-s fixed gap	0.03 (0.13)	--	0.03 (0.10*)
Age - Gender	26-45 years old - male	--	--	0.09 (0.04*)
	46-65 years old - male	--	--	-0.25 (<0.001*)
	66-85 years old - male	--	--	-0.03 (0.45)
Age – Number of lanes	26-45 years old - 2lane	--	--	-0.01 (0.74)
	46-65 years old - 2lane	--	--	0.10 (0.02*)
	66-85 years old - 2lane	--	--	0.13 (<0.001*)
Age - Vehicle speed	26-45 years old - 25mph	--	--	-0.13 (<0.001*)
	46-65 years old - 25mph	--	--	0.15 (<0.001*)
	66-85 years old - 25mph	--	--	-0.04 (0.30*)
Gender - Vehicle speed	Male - 25 mph	--	--	-0.06 (0.05*)
R^2		12.2%	11.7%	30.4%
Adjusted R^2		10.9%	10.8%	27.9%

*Note: * indicates the parameter has a significant effect on the response variable.*

<u>Crossing Success Rate</u>

The crossing success rate was calculated to identify which scenarios presented safety issues for the subjects performing the crossing maneuvers in the VR experiment. The worst crossing success rate of 81.2% was observed for the subject group that participated in the scenario with the 25-mph vehicle speed and short constant 3-s gap in the one-lane street. In contrast, perfect crossing success rates were observed for subjects in the 15-mph scenario with the "longer" 5-s gaps in the one-lane street and the variable gaps in the two-lane street. The effect of the independent variables on the probability of a subject being hit by a vehicle when crossing the street in the VR simulation was studied using a logit model. The response variable was defined as one if the subject was hit by a vehicle during the crossing maneuver, and zero otherwise. Table 4 shows the results for the logit model.

The significant variables in the logit model are the *age*, the *vehicle speed*, the *gap accepted*, the *fixed 3-s gap*, and the *walking speed*. The estimated coefficient for each variable represents the direct effect of that variable on the probability of the subject being hit by a vehicle in the simulation. The model indicates that the probability for the pedestrian being hit by a vehicle increases with the age of the subject, when the vehicle speed is higher (25 mph), and when the vehicle gap is fixed at 3-s (the shortest value). In contrast, the probability for the pedestrian being hit by a vehicle decreases with increases in the gap accepted to cross and the walking speed. The *gapfixed-3s* factor had the greatest impact on the probability of a hit when crossing the street. Not surprisingly, pedestrian speed is a determining factor in whether a successful crossover occurs, but we can see that the age factor, although marginally significant is also present.

Table 4 – Logit Model for the Probability of a Subject Being Hit by a Vehicle

Parameter	Coefficient	Standard error	p-value
Age	0.467	0.273	0.086*
Gender	-0.793	0.614	0.196
Vehicle speed	0.123	0.052	0.018*
Gap accepted	-0.615	0.337	0.068*
Gap seen	0.009	0.007	0.175
Gap fixed-3s	2.186	0.748	0.003*
Walking speed	-1.352	0.355	< 0.001*
Log-likelihood	-49.246	**Pseudo r-square**	0.35
p-value	< 0.0001		

*Note: * indicates the parameter has a significant effect on the response variable.*

4. Conclusions and Recommendations

This research studied the gap acceptance and walking speed of pedestrians when crossing an urban street at a mid-block location by using VR simulation. The main conclusions of the study are:

1. Subjects watched about 5 gaps on average before making the decision to cross the street. Older subjects from the 66-85 years old group had the greatest problem to cross the street as represented by the highest number of gaps watched before crossing the road, with a 58% difference with respect to the average.
2. Subjects accepted a gap of 4.5 s to cross the street on average. The gap accepted to cross the street increased with the number of lanes and decreased with the vehicle speed and the number of gaps the person watched before crossing. The number of lanes can be related to increasing difficulty due to the larger crossing distance. The number of gaps seen can be related to an impatience factor due to the increasing waiting time and to a learning process by having the chance of watching more vehicles.
3. The *age* and *gender*, the *number of lanes*, and the *gap fixed* were found to be significant factors to explain the walking speed when crossing a street. The interactions between age and the gender, the number of lanes, and the vehicle speeds also were deemed significant.
4. The worst performance when crossing the one-lane street was recorded on scenarios with the higher vehicle speed, the short constant 3-s gap, and for persons in the 66-85 age group. The probability of being hit by a vehicle when crossing the street increased with the age of the subject, on higher vehicle speeds, and shorter gaps between vehicles. In contrast, the probability for the pedestrian being hit by a vehicle decreases with increases in the gap accepted to cross and the walking speed.

It is recommended as future research work to expand the street crossing VR experiment in this research by studying the nature of the behavior and performance of drivers and pedestrians when crossing the street on other road geometric conditions, such as on curves, unsignalized intersections, and roundabouts.

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