STUDY OF GAP ACCEPTANCE AND WALKING SPEEDS OF PEDESTRIANS USING VIRTUAL REALITY SIMULATION

SAFER SIM

SAFETY RESEARCH USING SIMULATION

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16. Abstract

The focus placed on pedestrian safety is based on the alarming increase in fatalities in the U.S. in recent years. The 6,283 pedestrian fatalities observed in 2018 was the largest number on record from the previous 28 years. The study of pedestrian behavior and the evaluation of new and innovative pedestrian safety countermeasures are needed to reduce road-related fatalities. The objective of this study was to carry out a roadway crossing experiment using virtual reality (VR) simulation equipment. The study analyzed the behavior of pedestrians when making the decision to cross at an uncontrolled location on a one-lane and a two-lane urban street. The goal was to measure the ability of the subjects to detect safe vehicle gap times in traffic to cross the road and their walking speeds when crossing.

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Acronyms

AASHTO	American Association of State Highway and Transportation Officials
DOT	Department of Transportation
EDC	Every Day Counts
FHWA	Federal Highway Administration
ft/s	feet per second
IRB	Institutional Review Board
mph	miles per hour
MUTCD	Manual on Uniform Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
NCSA	National Center for Statistics and Analysis
NHTSA	National Highway Transportation Safety Administration
PRHTA	Puerto Rico Highway and Transportation Authority
STEP	Safe Transportation for Every Pedestrian
TRB	Transportation Research Board
TTA	time-to-arrival
UPRM	University of Puerto Rico at Mayagüez
US	United States
US-DOT	United States Department of Transportation
UTC	University Transportation Center
vph	vehicles per hour
VR	Virtual Reality

Abstract

The focus placed on pedestrian safety is based on the alarming increase in fatalities in the U.S. in recent years. The 6,283 pedestrian fatalities observed in 2018 was the largest number on record from the previous 28 years. The study of pedestrian behavior and the evaluation of new and innovative pedestrian safety countermeasures are needed to reduce road-related fatalities. The objective of this study was to carry out a roadway crossing experiment using virtual reality (VR) simulation equipment. The study analyzed the behavior of pedestrians when making the decision to cross at an uncontrolled location on a one-lane and a two-lane urban street. The experiment included eight scenarios showing different vehicle speeds and vehicle gap values. The goal was to measure the ability of the subjects to detect safe vehicle gap times in traffic to cross the road and their walking speeds when crossing. Comparisons between gender and age groups were made based on the factors measured in the experiment. The average time of the gaps taken by the pedestrians varied from 4.5 to 4.7 s for males and from 4.4 to 4.8 s for females in the one-lane crossing setting. For the two-lane crossing setting, the average time of the gaps taken increased from 6.6 to 7 seconds for males and from 6.4 to 6.7 s for females. The average walking speed varied from 4.11 to 4.75 ft/s depending on the vehicle gap and speed combinations. Although no major differences were observed between the male/female speed distributions, it was found that 7% of the female population needed to address the crossing at a faster pace than the male group. The age group with the lowest crossing success rate of 89.6% was found for the 66-85 age group when crossing the one-lane road. This result indicates that older pedestrians are most exposed to traffic accidents when crossing at an uncontrolled location, especially when facing high vehicle speeds. The results from this initial experiment using the VR headset demonstrate the potential benefits and promise of the use of this new technology to study human behavior in a controlled scenario. The results show that the recent advances in VR have improved the fidelity of the technology allowing measurement of human factors that reflect real-life values.

1.Introduction

1.1 Pedestrian Fatalities and Fatality Rates in the United States

Nationwide forums have been established in recent years to discuss the increasing numbers of pedestrian fatalities in the United States (U.S.), to better understand pedestrian gap acceptance for different vehicle approach speeds in urban settings, and to promote the identification and implementation of effective countermeasures. The focus of these dialogues has been on the study of the roadway circumstances and the related behavioral factors that cause these fatalities with the intention to evaluate the potential of road geometric design modifications, new or improved safety treatments, and education strategies that can effectively modify road user behavior or performance.

The higher focus placed on pedestrian safety is based on the alarming increasing numbers of fatalities in the U.S. in recent years. The following pedestrian fatality crash data are from the years 2009 to 2019. Pedestrian fatalities increased from 4,109 in 2009 to 6,283 in 2018, a 53% increase. Meanwhile, the overall road-related fatalities in the country increased by just 2% during the same period (GHSA, 2020). This is accentuated by the fact that the number of pedestrian fatalities in 2018 was the highest recorded since 1990, according to the National Highway Traffic Safety Administration (NHTSA, 2020). A recent report from the National Center for Statistics and Analysis (NCSA, 2020) reported a 2.7% decrease in pedestrian fatalities for the year 2019 compared to 2018, providing a pause in the aforementioned disturbing trend. Notwithstanding this positive change in the national trend, 24 states still experienced in 2019 an increase or remained at the same number of pedestrian fatalities. Figure 1 shows the pedestrian fatalities observed for 2019 in the U.S., including Puerto Rico. California (972), Florida (713), Texas (649), New York (268), and Georgia (236) were the five states with the highest numbers of pedestrian deaths in 2019, accounting for 45% of the total in the U.S. while having about 36% of the total population. The top five states that recorded the highest reduction in pedestrian fatalities from 2018 to 2019 were Pennsylvania (50), Louisiana (46), Indiana (41), Georgia (26), and Arizona (24), an equivalent of 187 fewer fatalities in those states alone. The total reduction observed in the U.S. for that period was 185 deaths, so the net effect of the 2018-2019 change in pedestrian fatalities for the other 47 U.S. locations was +2.

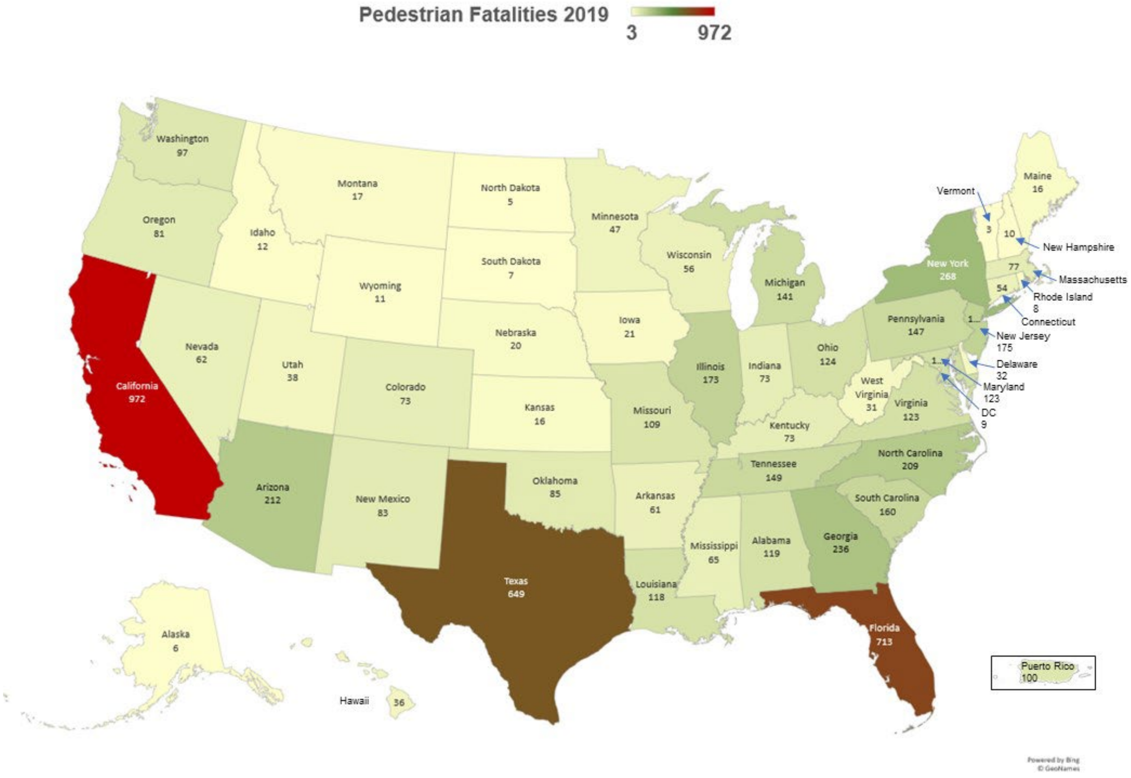

Figure 1 - Pedestrian Fatalities in the U.S. for the Year 2019

It is expected that the states with the highest population figures will also have the highest number of fatalities (the actual correlation between the two values is 0.94). Therefore, the fatality rate is a preferred statistic for making comparisons between locations because it accounts for the exposure level. For example, Puerto Rico had 100 pedestrian fatalities and Washington state had 97 pedestrian fatalities in 2019, which will position the two locations in the 20th and 21st highest positions in the U.S., respectively. However, Washington state had a population of 7.6 million in 2019, while Puerto Rico had a population of 3.19 million. Therefore, Puerto Rico's population is 2.4 times lower than that of Washington and 3.3 to 12.4 times lower than those of the top five states in pedestrian fatalities in the U.S. The analysis of traffic fatalities must account for the exposure effect. In this comparison, the impact of pedestrian fatalities is higher for Puerto Rico than for Washington state, even though their frequencies are similar.

For the safety analysis of motor vehicle crashes, the number of fatalities is divided by the exposure, as represented by the number of vehicles passing an intersection or the vehicle-miles traveled along a road segment. The miles traveled by pedestrians are not typically recorded, therefore the exposure effect is indirectly measured by the population. The pedestrian fatality rate might present a different story than the frequency, which merits analysis as well. Figure 2 shows the pedestrian fatality rate per 100k inhabitants for 2019 in the U.S., including Puerto Rico.

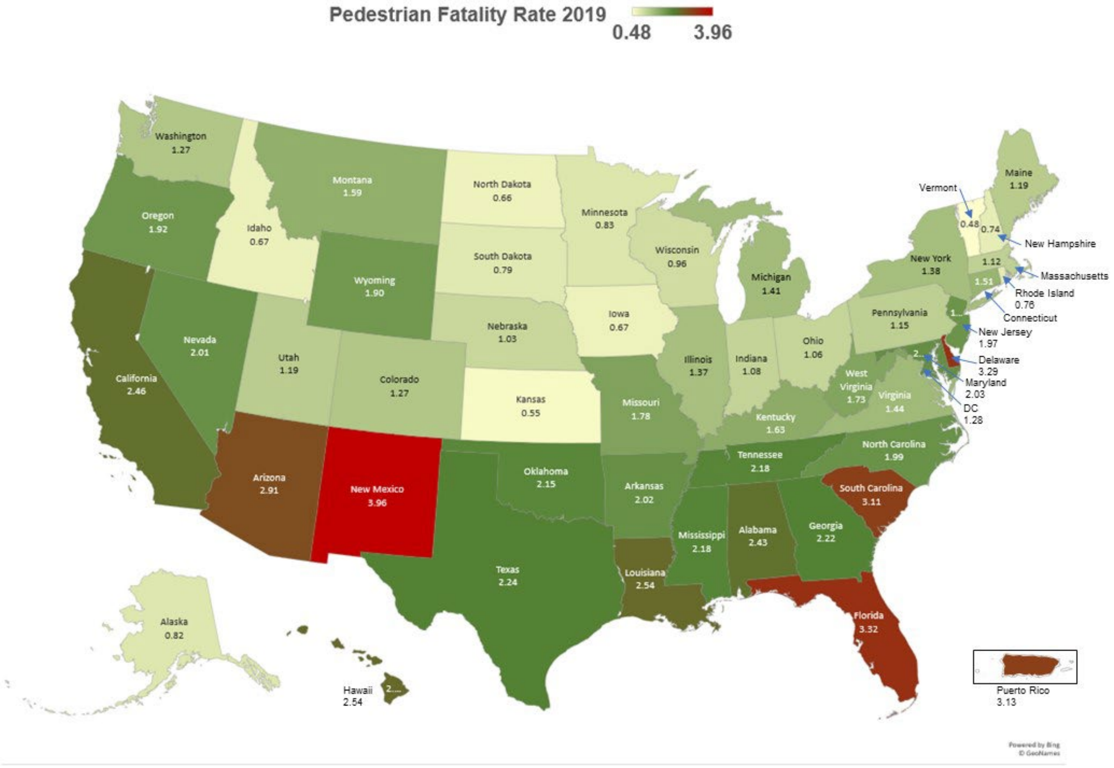

Figure 2 - Pedestrian Fatality Rates in the U.S. for the Year 2019

The five states with the highest pedestrian fatality rates per 100k inhabitants in 2019 are New Mexico (3.96), Florida (3.32), Delaware (3.29), South Carolina (3.11), and Arizona (2.91). The overall pedestrian fatality rate for the U.S., including Puerto Rico, is 1.90, showing a 3.3% reduction from the 2018 rate of 1.97. If Puerto Rico is included in the ranking, the territory will occupy the fourth overall position with a fatality rate of 3.13 (even though the 2019 rate for the territory was 13.8% lower than for 2018). It is noteworthy that out of the top 10 positions in terms of fatality rate, eight locations show reductions up to 27.9% (highest value for Louisiana) compared with 2018. The overall picture based on the fatality rate is more promising than for the frequencies, in the sense that only 19 states show an increased rate compared with 2018. On the other hand, 31 states have pedestrian fatality rates higher than the 2019 U.S. fatality rate.

The U.S. locations with a disproportionate increase in the number of pedestrian deaths and those with high fatality rates should increase their efforts to raise the level of concern and attention to pedestrian safety. The focus must be directed to the study of the main factors and circumstances associated with the deaths of vulnerable road users in those locations to identify patterns in the behavior and performance of pedestrians and evaluate the potential benefits of innovative safety countermeasures for the highway system. The Every Day Counts (EDC) initiative of the Federal Highway Administration (FHWA) is a state-based model to identify and rapidly deploy proven, yet underutilized innovations to shorten the project delivery process, enhance roadway safety, reduce traffic congestion, and integrate automation (FHWA, 2020). The innovations promoted by the EDC program can assist in saving resources, money, time, and, most importantly, the lives of road users. The Safe Transportation for Every Pedestrian (STEP) is one of the EDC initiatives, focusing on the systemic application of cost-effective countermeasures with known safety benefits to reduce pedestrian fatalities at both uncontrolled and signalized crossing locations (FWHA, 2020). To improve pedestrian safety, the STEP program promotes seven countermeasures, named “*the spectacular seven*”, which include road diets, pedestrian hybrid beacons, pedestrian refuge islands, raised crosswalks, crosswalk visibility enhancements, Rectangular Rapid Flashing Beacons (RRFB), and leading pedestrian intervals (FHWA, 2020).

1.2 Research Problem Statement

Road crashes are random and rare events. An effective safety analysis must be comprehensive and consider the impact of many factors related to the road, the vehicle, and the road user. These factors, alone or in combination, have a significant impact on both the frequency and severity of crashes. Some of the major factors related to crashes are the roadway type and its geometry, the traffic conditions and the road context under which it operates, the climate, the distribution of vehicle types and their condition, and the characteristics, experience, behavior, and performance of road users. The numbers of pedestrian deaths and injuries occurring around the world are already at tragic proportions, and the projections are that the situation will be worse in the future if no immediate actions are taken.

The United Nations Road Safety Collaboration (UNRSC, 2020) indicates that 46% of the 1.3 million annual road fatalities happening worldwide are from pedestrians, cyclists, and motorcyclists. Their study about the roadway conditions in 54 countries found that 92% of roads do not provide pedestrian crossing facilities at locations where pedestrians cross the road in the presence of traffic traveling at 25 mph (40 km/h) and at 22% of the poorly signed or maintained. In the case of pedestrian fatalities in the U.S., NCSA identified that around three out of each four of these events occurred in urban areas, during dark conditions, and at locations outside of intersections (NCSA, 2018). About one-third of the road fatalities in Puerto Rico are pedestrians, with 90% of these events occurring outside of intersections, and 88% are related to an improper action or traffic law violation made by the pedestrian (PRHTA, 2018). Zegeer et al. (2001) studied crash data from the years 1994-1998 from 28 U.S. cities and established that drivers failing to yield represented 41.5% of pedestrian crashes in marked crosswalks and 31.7% in unmarked crosswalks.

Also, improper pedestrian behavior was found to contribute to crashes. Other contributing factors include road environment characteristics, facility and lighting conditions (FHWA, 2017). Retting found that 59% of the pedestrian-related fatalities in 2018 in the U.S. occurred on a non-freeway arterial, 22% happened on local and collector streets, and 16% on freeways). In terms of pedestrian characteristics, the fatalities for men increased by 3.0%, and the fatalities for women increased by 4.8% in 2018 compared to 2017 (Retting, 2019). The 45-54 age group had the highest number of pedestrian fatalities and the 55-64 age group had the second highest number. The Puerto Rico Strategic Highway Safety Plan 2019-2023 (PRHTA, 2018) identified that the profile of pedestrian deaths on Puerto Rico roads was a 55-year-old male walking along the roadway. Puerto Rico's Safety Plan includes as a priority the implementation of planning and engineering countermeasures to reduce pedestrian fatalities and injuries. It is essential to study the human factors that are related to the pedestrian fatalities on our roads and specific maneuvers and decisions that users (both drivers and pedestrians) make frequently in order to develop and identify potential safety treatments that improve pedestrian safety.

The focus of this project is the study of pedestrian behavior during roadway crossing events on uncontrolled crossings. An uncontrolled crossing (at midblock or at an unsignalized intersection) is one of the most dangerous scenarios for a pedestrian. Each pedestrian must be able to evaluate the gaps available in the moving traffic in order to start and complete the roadway crossing maneuver in a safe manner without the assistance of traffic signals or stop signs. The vehicle gap is defined as the time difference between the leader and follower vehicles with reference to the pedestrian path. Conflicts and crashes at an uncontrolled crossing can be influenced by excessive vehicle speeds, inadequate conspicuity/visibility, drivers not yielding to pedestrians, and insufficient separation from traffic. The visibility of the pedestrian (or the drivers) can be affected by the road geometrics before and at the crossing location, vehicle gaps and speeds, lighting conditions, glare effect on drivers, presence of on-street parking, and vehicles with tinted glass. Males showed less waiting time and caused more motor vehicle conflicts than females (Ferenchak, 2016). Older pedestrians have reduced risk perception, more prolonged waiting times when crossing, and shorter gap distances lead to deciding not to cross. (Hamed, 2001; Holland and Hill, 2007; Shi, 2020). A video study of pedestrian crossing behavior found that the vehicle size also influences the accepted gap and that males and middle-aged pedestrians tend to accept the smallest gap in traffic (Ravishankar and Nair, 2018).

Much of the existing literature related to the evaluation and analysis of pedestrian behavior depended on the capability of carrying out observational studies in the field using manual data collection or video recording efforts. The benefit of observational studies is the direct collection of the user behavior as it occurs in real life, but the main drawbacks are the need for setting up the equipment at every location, obtaining the necessary combination of factors during the study, the cost associated with the data collection effort, and the safety of the collectors, the equipment, and the users. The development and recent availability of new simulation technologies, like virtual reality (VR) headsets and environments, has increased the opportunities for researchers to develop new experiments that will allow the collection of behavioral data for pedestrians and other road users in controlled and safe environments, while accounting for the many factors that affect road user performance. The capability and fidelity of these new technologies to simulate real roadway situations and obtain comparable and adequate data need to be carefully tested and evaluated.

1.3 Research Objectives

The study of pedestrian behavior and performance and the development and evaluation of new and innovative pedestrian safety countermeasures are needed to reduce road fatalities. The general objective of this study was to develop a roadway crossing experiment using VR simulation equipment to analyze how pedestrians make the decision to cross at an uncontrolled location on an urban street. Because there was no traffic control device to assist them in this decision, each subject had to analyze the existing roadway and traffic operating conditions to decide when an acceptable gap in the vehicle stream was available to safely cross the road. The study analyzed the ability of the subjects in the experiment to detect safe vehicle gap times to cross the road at the uncontrolled crossing and their capacity to respond to hazardous roadway situations. Pedestrian behavior and performance, in terms of the gap acceptance decision and walking speeds, were recorded and analyzed for each subject in the VR study. The specific objective was to identify differences between subject groups about the crossing times, the mean walking speeds, and the time and speed variance. The experiment included the capacity of detecting when a subject was hit by a moving vehicle when crossing. A variable named crossing success rate was calculated with the objective of comparing the crossing performance between subjects under varying conditions (one-lane street vs. two-lane street), traffic speed (15 mph and 25 mph), and constant vs. variable vehicle gaps.

The experimental design for the study included males and females divided into four age groups with the objective of making comparisons and being able to identify at-risk pedestrian groups from the sample. Although the initial objectives for the experimental design also included identifying sub-samples composed exclusively of elderly subjects and persons with diverse mobility (e.g., people using canes, people in wheelchairs, etc.), the impact of COVID-19 due to the declaration of the pandemic in March 2020 affected the research plan. Contacts were made with a local club of mostly retired persons and the Office of the Defender of the People with Disabilities of the government of Puerto Rico before the declaration of the pandemic, but these activities were postponed for a later time due to the strict health restrictions imposed by the Government of Puerto Rico and the university administration. The VR simulation experiment was conducted by the research team following strict equipment cleaning procedures and physical separation between the research team and the subjects possible. The handling of the two aforementioned special interest subject groups requires special care and attention and the need to move the VR equipment outside of the university facilities to carry out the simulation experiments. In order to preserve the health of the subjects and the members of the research team, it was decided to conduct the experiment using a balanced design with mostly voluntary subjects from the university community.

1.4 Report Organization

The organizational structure of this report consists of five chapters. Chapter 2 contains a review of published literature related to crash statistics, gap acceptance, walking speeds, and VR experiments. Chapter 3 explains the methodological procedure used in this investigation. Chapter 4 includes the results of the statistical analysis of the VR simulator data. Lastly, Chapter 5 provides conclusions and research recommendations. References, acknowledgments, and appendixes are included at the end of the report.

2. Literature Review

This chapter provides a summary of pertinent literature related to pedestrian safety, crash statistics, and human factors that were reviewed for this study. The review included the use of crash databases and reports with statistical information related to pedestrian fatalities in the U.S. and Puerto Rico.

2.1 Crash Statistics

During 2018, 74% of the pedestrian fatalities in the U.S. occurred at non-intersections, implying that most of the safety issues are related to pedestrians preferring direct routes across segments and/or mid-block crossings. Utilizing mid-block locations to cross a road results in a higher potential risk, considering the pedestrian time needed to safely cross the street weighed against their perception of the approaching vehicles' speed. It is essential to research pedestrians' crossing behavior and their interaction with vehicles so that feasible safety countermeasures can be identified. Contributing factors that affect the pedestrian gap acceptance and motorist yield decisions include the vehicle speed, the pedestrian walking speed, the distance between the vehicle and the crossing, the vehicle type, the waiting time for a safe gap in traffic, and the pedestrian age and gender.

Cardona (2020) reviewed U.S. pedestrian crash data, including Puerto Rico, for the years 2007-2016. The review found that a significant amount of crashes occurs in the dark with and without lighting. The times between 6:00 PM and 6:00 AM were the hours with the highest numbers of pedestrian fatalities in the data. The increase in each hour was more significant until 10:00 PM, when it began to decrease; however, until 11:59 PM, the amount of deaths continued to be higher. On the other hand, at dawn, the number of deaths started to decrease. During the hours of 7:00 AM to 4:00 PM, the crashes with pedestrians were lower. Also, it was observed that 75% of the pedestrian fatalities occurred in urban areas. Atmospheric conditions associated with crashes show that pedestrians tend to have more collisions under normal weather conditions. During severe weather conditions, there are usually no pedestrians on the roads; therefore, fewer crashes occur during those events (Cardona, 2020). The thesis “Analysis and Evaluation of Crashes Involving Pedestrians in Puerto Rico” by Lynnette Alicea (was used as a framework to perform the analysis of the crash data mentioned earlier).

2.2 Effect of Age and Gender Factors

The pedestrians' age and gender directly influence their walking behavior and performance. When analyzing road-related fatalities, one of the main factors to consider typically is the person's age. Children under 15 years old and adults over the age of 65 are considered most vulnerable in pedestrian crashes. Out of the total pedestrian fatalities, 4% of victims were under 15 years old and 30% were adults over 65 years old (NCSA, 2016). It can be inferred that, as an age-related factor, many crashes involving children occur because they fail to perceive the actual risk when crossing a road. Most children receive some form of training either at school or at home before beginning to cross a roadway without adult supervision. On the other hand, age affects adults over 65 years old directly, as their capacity for mobility is more limited than for younger pedestrians and their walking speed is typically slower than average. Additionally, most of these adults develop health conditions that also affect their mobility. Older pedestrians have decreased risk perception, longer waiting times, and larger minimum gap acceptance when crossing a street (Hamed, 2001; Holland and Hill, 2007). Studies have found that pedestrians between 21 and 30 years old are the fastest-walking age group (Tarawneh, 2001). Older pedestrians make more unsafe decisions, whereas younger pedestrians are more willing to violate regulations (Ferenchak, 2016).

Gender is another important factor when analyzing pedestrian behavior and performance, such as the time waiting for a gap and the tendency towards accepting risk (Hamed, 2001; Ferenchak,2016). Males are associated with 68.9% of the total pedestrian fatalities (NCSA, 2016). Studies have also found that male pedestrians have a low perception of risk when crossing a roadway in the presence of motor vehicles; thus, they are more willing to make riskier crossing decisions and violate regulations than their female counterparts (Holland and Hill, 2007). Males also tend to wait shorter amounts of time than female pedestrians before crossing a roadway (Ferenchak, 2016). They also exhibit faster walking speeds than their female counterparts, possibly related to their shorter waiting times (Tarawneh, 2001).

2.3 Walking and Crossing Speeds

The needs and abilities of pedestrians when walking along a roadway or when making the decision to cross a roadway vary significantly with age and is dependent also on the health and physical conditions of the person. The average walking speed is 4.0 ft/s and may be used to evaluate the sufficiency of the pedestrian clearance time approximately (MUTCD, 2009). Nevertheless, these average values cannot be assumed to correctly represent the performance for all the population groups, nor should they be used indiscriminately in road design for all conditions. Sixteen percent of the population of the United States was 65 or older in 2018 (Roberts, 2018). The walking speed for elderly people is well below the average value at approximately 2.8 ft/s, putting these road users in a riskier situation when crossing road facilities (FHWA, 2006). People with limited mobility capacity (e.g., persons with disabilities and persons who use assistive devices such as canes, walkers, or wheelchairs) represent 12.7% of the population of the United States and most probably exhibit a slower performance when crossing a road.

Chandra and Bharti (2013) observed seven roadway locations in India using video and concluded that the speeds used by pedestrians to cross a road were higher than the speeds used when walking along the roadway, irrespective of gender. One interesting conclusion from the Chandra and Bharti study was that walking speeds in India were found to be different from results from other countries. This could present the need for considering the local conditions and pedestrian behavior and culture when using national or typical values for designing roadway facilities. Another study observed crossing maneuvers of 1,191 subjects (60.1% females); however,97.5 % of the elderly pedestrians could not cross the street safely (Duim et al., 2017). The reduced walking speed of older people has been associated with slow decision making, as well as visual and hearing impairments (Asher et al., 2012; Holland and Hill, 2010). Knoblauch et. al (1996) observed sixteen crosswalks in four urban areas to estimate the walking speeds and start-up times of pedestrians. Their study found that the 15th percentile speed for pedestrians between 14 and 64 years old was 4.09 ft/s, and that it was 3.19 ft/s for older pedestrians. The walking speeds were found to be affected by the number of pedestrians in a crossing platoon, the weather conditions, and roadway-related factors such as the functional classification, vehicle volumes, road width, signal cycle length, ped signal timings, and the presence of medians, curb cuts, on-street parking, and right-turn-on-red maneuvers. Current national guidelines in the Manual on Uniform Traffic Control Devices (MUTCD) for timing pedestrian signals at an intersection recommends the use of a walking speed of 3.5 ft/s under typical conditions (FHWA, 2012). The MUTCD also recommends the use of a lower walking speed for the calculation of the pedestrian clearance time in intersections with the presence of slower pedestrians or people using wheelchairs. A value of 3 ft/s is recommended by the MUTCD to verify if the total of the walk interval and the pedestrian clearance time is sufficient to allow the pedestrian to perform the crossing maneuver.

2.4 Gap Acceptance Behavior

The study of the various aspects of pedestrian movements is a significant criterion in safety analysis, traffic flow modeling, and assessment (Tanariboon and Guyano, 2010). Pedestrians must be able to make crucial decisions when crossing a road. These decisions focus on accepting or rejecting a gap, known as the distance between two consecutive cars allowing pedestrians to pass a crosswalk. Dividing the crossing distance by the walking speed and then adding the outcome to the start-up time determines the proper gap for a crosswalk (Várhelyi, 1996). The safety related to a specific gap value in traffic has been linked to the time to arrival (TTA) of the approaching vehicles, and the vehicle approach speed is a significant factor in the selection of the size of the chosen gap (Petzoldt, 2014). At higher vehicle speeds, pedestrians tend to make riskier crossing decisions and accept smaller gaps. In cases when a pedestrian wants to cross more than one lane on a road, there might not be a proper gap. The pedestrians' behavioral pattern in this situation approaches the use of a rolling gap (Boroujerdian and Nemati, 2016). This behavior means that a pedestrian when crossing a multi-lane street does it in a pattern using a distinctive gap for every lane (Zhao, 2012). Yannis (2010) found that the pedestrian gap acceptance depends more on the longitudinal distance from the vehicle to the pedestrian, pedestrian gender, the vehicle length and the presence of illegally parked cars. Kadali and Vedagiri (2013) conducted a gap acceptance study in Hyderabad, India, and concluded that the pedestrian gap acceptance depends on the pedestrian speed, the vehicle speed, the pedestrian direction, the rolling gap, and the pedestrian’s age.

2.5 Virtual Reality Simulation

Virtual reality has the capability to provide the user with a role-playing situation with almost complete sensory immersion in a controlled environment. The system characteristics include immersion, allowing the user to experience activities from an internal perspective, and reactiveness, respective to observable variations based on the user’s actions (Schwebel et al., 2008). Simulation technologies have become a useful tool in transportation research to study human factors and behavior; the most remarkable examples are driving simulators. Simulators allow the reproduction of standardized scenarios and manage the parameters under investigation (de Winter et al., 2012). Pedestrian simulators that help to envision virtual roadway scenarios from the perspective of the pedestrians are currently being used as a powerful transportation safety research tool. Recent advances in VR technology now present opportunities for researchers to develop and carry out new realistic and engaging pedestrian studies that in the real world have significant safety, costs, or complexity implications (Shuchisnigdha et al., 2017).

The essential elements of VR are interactive simulation, implicit interaction, and sensory immersion as mentioned above. The user observes the environment through small monitors attached on a light-weight head-mounted device known as glasses, and the technology provides the option of adding controls or handles for a more reliable experience. The fidelity of the VR devices refers to the accuracy with which real sensory cues are reproduced (Kearney et al., 2007). Nevertheless, current VR setups will differ from recreating perfect real-world scenarios because computer display technologies are still imperfect, and not all the perceptual and contextual cues needed to recreate a real-world experience are known yet (Kearney et al. 2007). These VR devices are usually promoted commercially for gaming and entertainment purposes, but they are also being applied in medicine, architecture, defense, and art. The primary senses activated during the performance of a VR scenario are sight and hearing, allowing the user to experience roadway situations that, in real life, could be risky or even fatal. Even with the current limitations, VR technologies can be used to study the human brain and its reactions to sensory and cognitive cues (Kearney et al., 2007). Enabling pedestrians to encounter complex situations by being immersed in a virtual environment would allow researchers to study human factors, the differences in behavior and performance between pedestrians, roadway safety issues, the effects of new road design strategies, or new traffic control devices, among other benefits.

Shuchisnigdha et al. (2017) used an HTC Vive VR headset and a Unity 5 virtual environment to recreate an urban downtown setting with two-lane streets and a four-leg intersection with pedestrian crosswalks. The objective of their study was to obtain objective and subjective measures of subjects crossing the intersection at one of the 5.5-meter-long crosswalks. The average walking speed found for the 26 subjects in their study was 3.51 ft/s. The experiment observed that the subjects were hit by a vehicle in 10.8% of the crossing simulation runs. They concluded the fidelity of VR simulation allows obtaining objective measures of pedestrian behavior, such as average walking speeds, that match those measured in real-world situations.

3. Research Methodology

The research methodology consisted of the use of VR simulation technology to analyze the pedestrian behavior at an uncontrolled roadway crossing for a one-lane street and a two-lane street in an urban downtown environment. The study methodology included seven steps as shown in Figure 3.

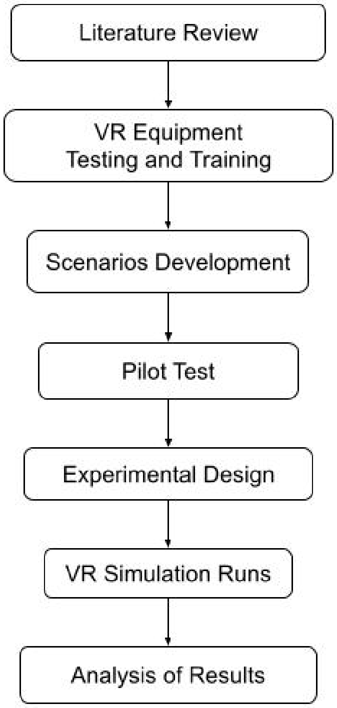

Figure 3 - Research Methodology

The first step consisted of a literature review on topics related to pedestrian fatality statistics, pedestrian behavior, walking speed, gap acceptance, and VR simulation, among other topics. The second step included the testing and training phase of the UPRM research team to learn the correct use of the VR equipment, how to set up the detection area in the room and how to calibrate the VR equipment. The testing and training phase was initially made with the HTC Vive headset and a desktop computer that were readily available for the research team. A second VR unit was later acquired, the HTC Vive Pro

Eye headset, that provides more capacity for having a larger detection area than the HTC Vive, and includes eye-tracking and wireless capabilities. Also, a gaming laptop was acquired with high computing capacity for better graphics processing for the VR equipment. The gaming laptop also improves the mobility of the VR equipment to carry out experiments outside the UPRM campus facilities. The specifications of the two VR headsets, gaming laptop, and desktop computer are provided in Section 3.1.

The next step included the development and programming of the simulation scenarios created with the Unity 2018.3.14f1 platform. A base scenario that represented a straight roadway segment in an urban downtown context was created. Buildings and sidewalks were added to both sides of the roadway. Two different versions of the urban street were created, a one-lane roadway and a two-lane roadway. Moving traffic was programmed in one direction coming from the left to the right in the simulation. The task required of subjects was to observe the gaps in the incoming traffic and cross safely to the sidewalk on the other side of the street. Once on the sidewalk at the other side of the street, the subject needed to walk back to return to the starting sidewalk. That process was repeated based on the experimental design. Once the programming of the simulation scenarios was completed, a pilot test was carried out to inspect the fidelity of the simulation, to check that the calculations for the response variables in the coding and the data recording were functioning, and to validate parameters for the experimental design to be used for the study. The experimental procedures included carrying out the simulation runs and asking the subjects to complete pre-test and post-test questionnaires to gather information about the subjects’ perception and attitude regarding their safety while crossing a road and to collect information about their experience during the VR simulation experiment. The descriptions of the simulation scenarios, the pilot test, the experimental design, and the experimental procedures are provided in Sections 3.2 and 3.3. Sections 3.4, 3.5, and 3.6 described the survey questions of the pre-test and post-test questionnaires, the sample description, and the response variables collected in the experiment, respectively.

3.1 Equipment

The operation manual of the HTC VIVE VR headset was reviewed and studied by the research team to understand the equipment operation, calibration, and setup. A literature review on the equipment was also performed to learn about different applications of the VR simulation and its benefits and limitations. The HTC Vive VR headset, shown in Figure 4, was first made available to consumers in April 2016. The VR headset has a detection zone of 11.5 ft x 11.5 ft (box size), which allows it to represent the crossing maneuver for the one-lane roadway scenario. Two Steam VR sensors installed on tripods at a height of about 5 ft are located at the corners of the detection box. The headset can be connected to detachable headphones to reproduce sounds during the VR simulation. The VR equipment also includes two handles, but these were not included as part of this experiment. The VR headset has a cable to connect to the computer. This cable has the length necessary to cover the entire detection box size. The technical specifications of the HTC Vive VR headset are included in Table 1.

(Source: https://www.vive.com/us)

Figure 4 - HTC VIVE Headset, Controllers, and Base Stations

Table 1 - Technical Specifications of the HTC Vive VR Equipment

Screen:	Dual AMOLED 3.6-in diagonal
Resolution:	1080 x 1200 pixels per eye (2160 x 1200 pixels combined)
Refresh rate:	90 Hz
Field of view:	110 degrees
Safety features:	Chaperone play area boundaries and front-facing camera
Sensors:	SteamVR Tracking, G-sensor, gyroscope, and proximity
Connections:	HDMI, USB 2.0, stereo 3.5 mm headphone jack, Power, and Bluetooth
Eye Relief:	Interpupillary distance and lens distance adjustment
Controllers:	SteamVR Tracking, Multifunction trackpad, Grip buttons, dual-stage trigger, System button, Menu button, and Micro-USB charging port
Room-scale:	Up to 11.5 ft x 11.5 ft
Base Stations:	Two (360-degree play area tracking coverage)

The research team decided to have an assistant walking next to the subject when using the HTC Vive VR headset to avoid issues with the cable being entangled with the subject's neck or body when turning around to return to the original position (the starting sidewalk). Also, the handler made sure the subject did not exceed the cable length. The research team understood that, although the cable had sufficient length to accommodate the one-lane crossing maneuver, the handler provided confidence to the subjects that no harm would happen inside the VR environment. The mere presence of the cable could potentially restrict the movement of subjects that became aware of it and could feel insecure walking on the VR thinking about reaching the full extension of the cable. During the test runs, some persons walked diagonally towards the same direction and eventually stepped outside the detection box when returning to the original sidewalk. The handler also had the responsibility of providing verbal instructions to the subject at the end of the simulation run in cases when the person walked diagonally in the detection area and needed to correct their position inside the detection box when returning to the starting sidewalk.

The UPRM research team acquired the new HTC Vive Eye Pro VR headset, shown in Figure 5. This new VR headset, released to consumers in 2019, is an expanded version of the HTC Vive Pro headset and includes native, built-in eye-tracking capabilities. The basic setup includes the VR headset, two handles, and two sensors, but this system has expansion capabilities to improve the VR simulation. The headset also comes with detachable headphones to reproduce sounds inside the VR simulation.

(Source: https://www.vive.com/us)

Figure 5 - HTC Vive Eye Pro Headset, Controllers, and Base Stations

The new headset has foveated rendering capabilities that produce higher fidelity VR images while requiring less processing power by rendering the parts of the scene that the subject is actually looking at in high resolution while lowering the resolution on images located on the peripheral vision (Hollister, 2019). Besides providing better resolution for the VR graphics and eye-tracking capabilities, the HTC Vive Pro Eye VR headset has the capability of adding more sensors to expand the detection box to an area of 32.8 ft x 32.8 ft. Also, the headset can add a mountable antenna to replace the cable that communicates with the computer. This option eliminates the mobility restriction and safety concerns of the connecting cable. The larger detection area allows the experiment to expand the urban roadway context to a two-lane crossing scenario. Two additional Steam 2.0 VR sensors and the wireless antenna were acquired with the headset. Table 2 presents the technical specifications for the HTC Vive Eye Pro VR headset.

One desktop computer and one gaming laptop computer were available for the setup of the pedestrian VR simulator and conducting the experiments. The gaming laptop is a Dell G7 model with an Intel Core i7-9750H processor, 32 GB of RAM memory, and an NVIDIA GeForce RTX 2070 graphics processor with 8 GB. The desktop computer is a Rave-PC model with an Intel Core i7-4770S processor, 16 GB of RAM memory, and an NVIDIA GeForce GTX 1080 graphics processor with 8 GB.

Table 2 - Technical Specifications of the HTC Vive Eye Pro VR Equipment

Screen:	Dual OLED 3.5-in diagonal
Resolution:	1440 x 1600 pixels per eye (2160 x 1200 pixels combined)
Refresh rate:	90 Hz
Field of view:	110 degrees
Audio:	Hi-Res-certified headset, Hi-Res-certified headphones (removable), high-impedance headphone support, and enhanced headphone ergonomics
Safety features:	Chaperone play area boundaries and front-facing camera
Sensors:	SteamVR Tracking, G-sensor, gyroscope, proximity, eye comfort setting (IPD) and eye-tracking
Connections:	USB-C 3.0, DP-1.2, Bluetooth
Eye Relief:	Lens distance adjustment
Controllers:	SteamVR Tracking 2.0, Multifunction trackpad, Grip buttons, dual-stage trigger, System button, Menu button, and Micro-USB charging port
Room-scale:	Up to 32.8 ft x 32.8 ft using four SteamVR Base Station 2.0
Base Stations:	Includes two 2.0 base stations, and two more were acquired to achieve the area's full capacity

3.2 Experimental Design

The experiment consisted of evaluating two urban roadway settings: a one-lane street and a two-lane one-direction street. The experimental design for the one-lane road simulation considered two independent variables: the traffic speed and the gap between vehicles. The speed used to generate traffic in the simulation was set at two values: 15 mph for Configuration 1 and 25 mph for Configuration 2.

Speed is a significant factor in crashes as it affects the driver's field of vision and the ability to react in time to avoid a crash. In the pedestrian’s point of view, the severity potential from a crash with a moving vehicle can be considered to be high even at speeds considered to be low for drivers. Teff (2011) indicates that the average risk of severe injury for a pedestrian struck by a vehicle is 10% at an impact speed of 16 mph, 25% at 23 mph, 50% at 31 mph, 75% at 39 mph, and 90% at 46 mph. The average risk of death for a pedestrian reaches 10% at an impact speed of 23 mph, 25% at 32 mph, 50% at 42 mph, 75% at 50 mph, and 90% at 58 mph (Teff, B., 2011). Therefore, the two speeds selected for the simulation will reflect typical city conditions in a low-speed road environment. The use of a constant speed will not allow vehicles to pass one another. As this is the first research study conducted by the UPRM research team with the VR equipment, the results from this study with traffic generated at two constant “low” speeds will provide a benchmark of pedestrian behavior. Future studies will include the effect of higher and variable vehicle speeds and more complex road configurations.

Each configuration had three scenarios with different vehicle gaps. Scenario 1 had variable gaps between vehicles, randomly generated in half-second increments, from a minimum of 2 s to a maximum of 5 s. Scenario 2 was defined with a fixed 3-s gap, and Scenario 3 was defined with a fixed 5-second gap. The decision to use constant 3-5 s gap values in separate scenarios was made to compare the behavior of the subjects in two extreme situations: a more hazardous traffic flow (1,200 vph) and a more relaxed traffic flow (720 vph).

The experimental design for the two-lane roadway setting used the same aforementioned two-vehicle speeds, but in only one configuration: 15 mph and 25 mph. Two scenarios were created with variable vehicle gaps, randomly generated in half-second increments, in a range of 2 to 8 s.

A pilot test for the one-lane roadway setting was carried out with eight subjects (four men and four women) within four age groups (18-25, 26-45, 46-65, and 66 or older). This test was used to determine statistically the number of subjects and the number of runs per subject that will be needed for the experimental design of the real simulation. Normality tests performed on the data obtained from the pilot test showed it did not follow a normal distribution. A new variable was then generated with the average of the gaps seen by the test subjects. A distribution fit test was performed, and it was determined that the new variable (average gaps seen) comes from a Weibull distribution. Based on the results of the pilot test, it was determined that at least 32 subjects (four men and four women for each of the four age groups) were needed to conduct the one-lane road setting, with each subject repeating each scenario at least four times, for a total of 12 simulation runs per person. Table 3 shows the description of the simulation scenarios used in the one-lane roadway setting.

Table 3 - Description of Scenarios for the One-lane Roadway Setting

Configuration 1			**Configuration 2**		
Scenario	**Gaps (s)**	**Traffic Speed**	**Scenario**	**Gaps (s)**	**Traffic Speed**
1	2 to 5	15 mph	1	2 to 5	25 mph
2	3	15 mph	2	3	25 mph
3	5	15 mph	3	5	25 mph

For the two-lane roadway setting, 16 subjects (two men and two women for each of the four age groups) were needed, with each subject repeating each scenario five times, for a total of simulation 10 runs per subject. Table 4 shows the description of the simulation scenarios used in the two-lane roadway setting.

Table 4 - Description of Scenarios for the Two-lane Roadway Setting

Configuration 3					
Scenario	Gaps (s)	Traffic Speed	Scenario	Gaps (s)	Traffic Speed
1	2-8	15 mph	2	2-8	25 ph

3.3 Description of Base Scenario

The base scenario consisted of an 885.8 ft (270 m) straight segment of a one-lane road located within an urban context, as shown in Figure 6. The road geometry and the city context were built using AutoCAD and SketchUp. Initially, a 2D base design of the one-lane road was created in AutoCAD. The design was imported to SketchUp, where the 3D environment was formally defined with the corresponding heights, textures, and colors.

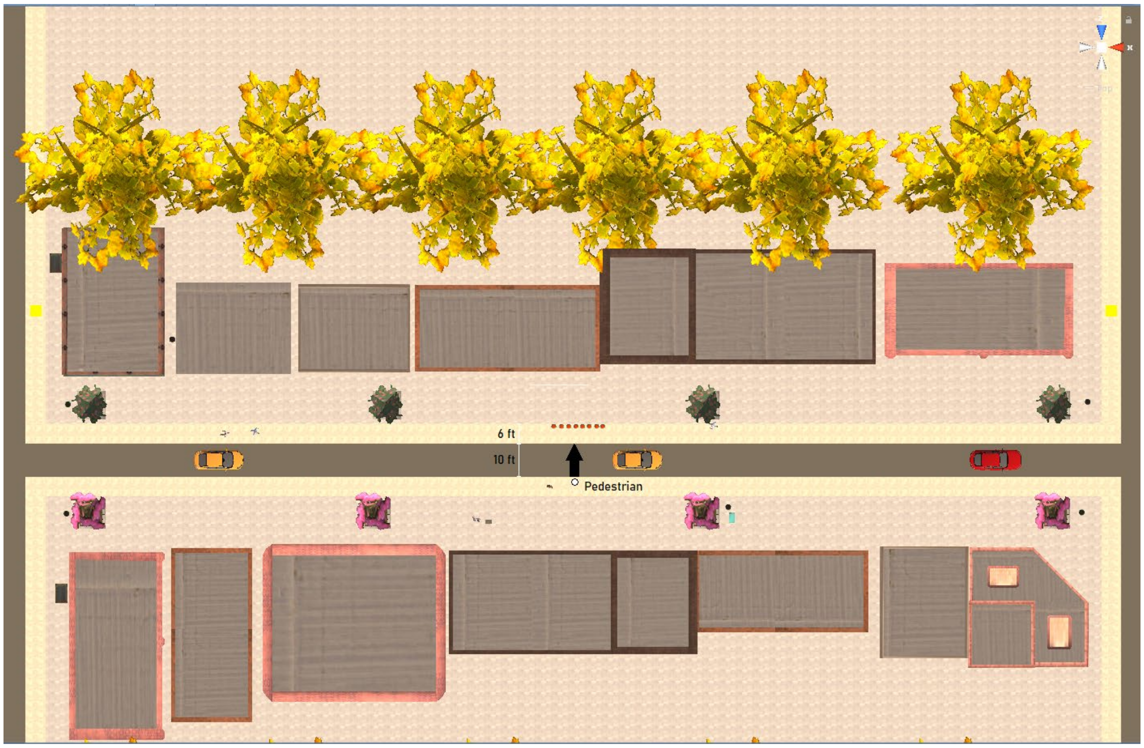

Figure 6 - Plan View of the One-lane Urban Roadway Context

Subsequently, the rendering of the design was improved in the Unity software to develop a more realistic environment by adding buildings, pedestrians, vehicles, traffic signs, trees, background, and traffic barrels to create an urban area. The typical roadway cross-section consisted of a 10-foot-wide lane and 6-foot-wide sidewalks. The scenario included buildings and sidewalks along both sides of the road. A buffer area was provided between the buildings and the sidewalks to provide better depth perception to the subjects in the VR simulation. Work zone barrels were located on the target sidewalk as a reference for the pedestrian to stop walking after crossing the road. Walking past the barrels would cause the subject to exceed the detection zone, interrupting the VR simulation. The pedestrian crossing location was established at approximately the mid-point of the road segment. The road network included two intersections with the main lane to provide the subject with a more realistic perspective allusive to small blocks (approximately 213 ft or 65 m long) of a representative city. The traffic in the simulation does not react to the presence of the crossing pedestrian. The Unity software was used to code the parameters for the moving vehicles, the pedestrian avatars, and other dynamic elements present in the VR simulation. Figure 7 shows a view of the VR simulation from the perspective of the subject standing on the origin sidewalk (before crossing the roadway) looking towards the incoming traffic from the left of the scenario.

A billboard display was added to the simulation to provide information to the subject in the VR simulation. Two types of information were provided during the simulation runs. The first line of information was active during the entire experiment indicating the trial number being conducted. This information was provided so the subject could be aware of how many trials remained to complete the experiment. The second line of information in the billboard was passive and was only activated when the subject was hit by an oncoming vehicle when crossing the road. In such cases, the blinking message “FUE ATROPELLADO” (YOU WERE HIT) in red capital letters appears on the display. The purpose of this message is to alert the pedestrian that the selected gap and the walking speed were not adequate to safely cross the road. The intent was to keep the subjects alert during the VR experiment to the fact that they were being evaluated during the crossing maneuver and kind of keep them "incentivized" to expend their best effort in meeting the goal (getting to the other sidewalk without being hit).

Figure 7 - Street View of the One-lane Road Context

To create the two-lane roadway setting, the single lane in the base scenario was duplicated and modified to include two 10-ft lanes, as shown in Figure 8. The two-lane road included pavement markings with white broken lines along the middle of the road to separate the traffic lanes, white traverse markings to identify the pedestrian crossing, and a pedestrian crossing warning sign. The broken lines between the lanes were drawn as 4 in wide and 5 ft long, and with a spacing of 15 ft between lines, according to guidelines in the MUTCD Part 3 Section 3A.06 (FHWA, 2012). The pedestrian crosswalk markings were drawn according to the guidelines in the MUTCD Part 3 Section 3B.18 (FHWA, 2012). The marking pattern included lines 1 ft wide and 10 ft long, with the width of the crossing greater than 6 ft. A W11-2 pedestrian crossing warning sign was situated on the right sidewalk, previous to the pedestrian crossing, according to the MUTCD Part 2 Section 2C.50. The traffic control devices were added only for aesthetic purposes to exhibit a real roadway setting, but the simulated traffic does not react (i.e., reduce speeds, stop, or change lanes) to the presence of the pedestrian crossing the road. The vehicles in the simulation were programmed to depart randomly and independently in each lane. As in the previous setting, the vehicles are coming in one direction from the left side. The billboard display was also added to provide the same two types of information as in the one-lane road setting. Figure 9 shows the two-lane roadway scenario from the perspective of the subject in the VR simulation.

Figure 8 - Plan View of the Two-lane Urban Roadway Context

Figure 9 - Street View of the Two-lane Road Context

3.4 Survey Questionnaires (Pre-test and Post-test)

The experiment followed the regulations established by the UPRM Institutional Review Board (IRB). The experimental procedures were approved by the IRB on November 21, 2019. During the recruitment phase and before starting the experiment, each subject was informed about the purpose of the research study, and the informed consent form was provided to each subject. After reading the form, the subject needed to sign the informed consent form to voluntarily participate in the experiment. A copy of the authorization letter from the UPRM IRB and the informed consent are included in the appendix.

The subjects that participated in the experiment were asked to fill out a questionnaire before and after the VR simulation runs. The pre-test questionnaire had eight questions in two sections. The objective of the first section of the pre-test questionnaire was to obtain the gender and age of the subject and to find out if the person suffered from motion sickness or from a health condition that would prevent him or her from safely carrying out the VR experiment. The second section of the questionnaire was used to determine the level of exposure as a pedestrian each subject had, the crash experience in the last five years, and their perception regarding safety when crossing a road. The pre-test questionnaire is included in the appendix.

The post-test questionnaire had seven questions, and its purpose was to request the opinion and perception of the subjects about the difficulty level experienced when crossing the road in the VR simulation considering the variability of the factors presented in the experiment (vehicle speed, gap and time between vehicles, the number of vehicles, and the width of the road). Also, the subjects were asked to provide comments about their comfort when using the VR headset, their opinion about the fidelity of the VR simulation, and recommendations about how to improve the experiment and the VR simulation. The post-test questionnaire is included in the appendix.

3.5 Sample Description

All the subjects that participated in the experiment were 18 years or older. A total of 48 subjects, divided into three groups of 16 subjects, were recruited. Table 5 presents the descriptive statistics of the age of the subjects recruited by gender and age group. Each group of 16 subjects was composed of eight men and eight women (two men and two women for each of the four age groups).

The first subject group watched the three simulation scenarios of Configuration 1 (one-lane road with 15-mph traffic). As indicated in Table 3, Configuration 1 had three different gap values, so each subject performed each scenario four times for a total of 12 simulation trials. The watching order of each simulation scenario was assigned randomly for each subject.

Table 5 - Descriptive Statistics for the Age of the Subjects in the Sample

Gender	Age	Average	Standard Deviation	Minimum Value	Maximum Value
Female	All	45.54	19.00	20	74
	18-25	21.67	1.84	20	25
	26-45	37.17	3.43	33	41
	46-65	53.33	8.66	46	64
	>65	70.00	3.29	66	74
Male	All	44.79	18.81	22	72
	18-25	24.17	1.33	22	25
	26-45	31.33	5.61	26	40
	46-65	54.83	6.94	46	62
	>65	68.83	2.14	67	72

The second group watched the three scenarios of Configuration 2 (one-lane road with 25 mph traffic), as described in Table 3. Each subject watched each of the three scenarios four times, in random order, for a total of 12 simulation trials per subject.

The third group watched the two scenarios described in Table 4 for the two-lane road setting (Configuration 3). Each scenario was repeated by each subject five times each, for a total of 10 simulation trials. The vehicle gaps generated in this configuration were random, so in each trial, the subject observed variable gaps in traffic at different speeds.

The first and second subject groups generated a total of 192 simulation trials each, for a total of 384 observations. The third subject group generated a total of 160 observations.

The total number of trials generated in the VR simulation experiment was 544 observations.

3.6 Data Recording and Measurements

After the subject completed the pre-test questionnaire, instructions on how the VR experiment was to be conducted were provided by the research team. After confirming with the subject, the VR headset equipment was shown to the subject and put on the subject's head with the help of the two research assistants. Once the VR headset was securely fixed and the subject gave verbal confirmation that he/she was comfortable with the device, the VR simulation was activated. Once the scenario was visible, the subject appeared standing on the starting sidewalk on the right side of the road, as shown in Figures 7 and 9. The subject was instructed to always wait for the first vehicle to pass the crossing location to start the simulation trial. The subject had to observe traffic from the sidewalk to wait for an adequate gap between vehicles before walking to the sidewalk on the other side of the road. Once the subject crossed the road and reached the other sidewalk, the traffic ceased to be generated in the simulation. The subject was then asked to return to the original sidewalk, and then the next simulation trial was started. Once all the trials were over for the subject, the VR headset was removed and cleaned by the research team following the manufacturer's recommendations, as part of the health procedures to prevent COVID-19 transmission between subjects. After the VR simulation was completed, the subject filled out the post-test questionnaire.

During each simulation trial, the master computer recorded the position and orientation of the subject's head and the position of all vehicles generated on the scenario at every time period. The simulation experiment collected the following performance variables:

1. **Number of gaps seen**: the number of gaps seen by the subject before crossing the roadway, including the gap taken (a measure of time waiting for a gap).

2. **Gap taken**: the size (in seconds) of the gap selected by the subject to cross the road.
3. **Average walking speed:** average speed calculated as the ratio between the distance walked on the pedestrian crossing and the time spent crossing it.
4. **Time spent**: the time it took each subject to cross the road (from the moment he/she entered the traveled way to the moment he/she exited the traveled way).
5. **Crossing success rate**: the ratio of the number of trials not impacted by a moving vehicle while crossing the road by the total number of trials performed by each subject.

4. Analysis of Results

The following chapter presents the discussion of the results obtained from the VR experiments. The discussion of the variables calculated for each road setting is presented in separate sections.

4.1 Gap Acceptance Analysis for One-lane Crossing Scenarios

The main objective of the VR experiment was to analyze pedestrian behavior when making the decision to cross a road in the presence of traffic at an uncontrolled location. Each subject needed to analyze the available gaps between the generated vehicles in the simulation to decide which gap was adequate to safely cross to the other side of the road. A variable of interest in this analysis is the number of gaps that each subject saw at each trial in the experiment. A larger number of gaps seen is indicative of a longer time waiting for an adequate gap in traffic. Tables 6 and 7 show the descriptive statistics of the number of gaps seen for the three scenarios observed for Configuration 1 and Configuration 2, respectively, aggregated by the eight demographic groups in the sample.

The experiment was designed for the collection of 8 trials (repetitions) per scenario for each demographic group. Each demographic group was composed of two subjects. The data from three trials of Configuration 1 and data from one trial of Configuration 2 were noted missing during processing and analysis. Therefore, a total of 380 observations were obtained for the one-lane road crossing setting (189 total data points for Configuration 1 and 191 total data points for Configuration 2).

Table 6 - Descriptive Statistics for the Number of Gaps Seen in Configuration 1

Vehicle Speed (mph)	Gender	Age	Scenario	Trials	Average	Standard Deviation	Minimum Value	Maximum Value
15	Female	18-25	1	8	5.50	1.93	3	9
			2	7	11.43	3.31	5	14
			3	8	2.75	1.16	1	4
		26-45	1	8	2.75	1.75	1	6
			2	8	5.00	3.42	1	10
			3	8	1.75	1.49	1	5
		46-65	1	7	10.57	19.70	1	55
			2	8	17.63	11.21	8	43
			3	8	1.50	0.76	1	3
		66-85	1	8	2.50	2.20	1	6
			2	8	36.25	37.70	4	112
			3	8	1.50	1.07	1	4
	Male	18-25	1	8	2.13	0.83	1	3
			2	8	5.13	5.00	1	14
			3	8	2.13	0.83	1	4
		26-45	1	8	2.75	3.37	1	11
			2	8	6.00	5.45	2	19
			3	8	1.25	0.71	1	3
		46-65	1	7	3.86	3.34	1	10
			2	8	6.63	4.44	1	13
			3	8	1.38	0.74	1	3
		66-85	1	8	3.63	3.93	1	13
			2	8	5.00	3.46	1	11
			3	8	1.63	0.74	1	3

The results from the 8 trials taken for the 66-85 male group from Scenario 2 in the Configuration 2 presented an excessively high number of gaps seen. The average number of gaps seen for this group was 133.38 when considering the 8 trials taken, with a maximum value of 395 gaps seen. The average value was 114.5% higher than the second highest average value in the entire sample in the total experiment, that was 36.25 gaps for the 66-85 female group, for Scenario 2 in the Configuration 1 (lower vehicle speed). Scenario 2 was purposely designed to represent the hardest crossing situation for the subjects with a constant 3-s gap between vehicles, so the fact that these scenarios generated the highest number of gaps, especially for the older age group, was not really unexpected. The notes taken during the experiment for the individual trials were revised for a more in-depth analysis. It turned out that there were two trials for this male group where the same subject took 390 gaps in one trial and 395 gaps in another. These two trials fall at more than 1.5 standard deviations above the mean value for this group (the original standard deviation of the gaps seen was 167.3). It was initially inferred that this subject, a 72-years-old male (the oldest person in the sample), possibly had concerns about crossing the simulated roadway in this complicated scenario and recognized his limitations to cross safely. But in the next two trials, the subject took only 9 and 5 gaps, so another plausible explanation was the potential for a learning effect on the use of the VR technology and the subject becoming accustomed to the experiment. The decision was to remove these two data points from the database as possible outliers.

Table 7 - Descriptive Statistics for the Number of Gaps Seen in Configuration 2

Vehicle Speed (mph)	Gender	Age	Scenario	Trials	Average Value	Standard Deviation	Minimum Value	Maximum Value
25	Female	18-25	1	8	1.75	1.39	1	5
			2	8	5.13	4.22	2	15
			3	8	1.38	0.74	1	3
		26-45	1	8	2.63	2.07	1	6
			2	8	5.00	2.39	2	9
			3	8	1.38	0.52	1	2
		46-65	1	8	2.38	1.30	1	5
			2	8	5.25	1.75	3	8
			3	8	1.00	0.00	1	1
		66-85	1	8	1.88	0.83	1	3
			2	8	8.25	4.17	4	16
			3	8	1.50	0.53	1	2
	Male	18-25	1	8	2.25	1.28	1	4
			2	8	15.25	16.67	5	55
			3	7	1.00	0.00	1	1
		26-45	1	8	2.25	0.71	1	3
			2	8	11.63	6.41	5	21
			3	8	1.50	0.53	1	2
		46-65	1	8	2.63	0.92	2	4
			2	8	7.38	5.95	2	21
			3	8	1.13	0.35	1	2
		66-85	1	8	6.25	5.50	1	19
			2	6 (a)	47.00	58.07	5	145
			3	8	11.63	23.00	1	68

Note (a) - two data points were identified as outliers in this group.

Figures 10 and 11 show the average number of gaps seen by the subjects in the one-lane road crossing. Figure 10 shows the box-plots of the gaps grouped by scenario and speed configuration. The data from all subjects per scenario was shown aggregated in this figure. As expected, the highest number of gaps seen were in Scenario 2. Scenario 2 had the vehicles generated with a short constant gap of 3 s, representing the hardest crossing situation of the three scenarios. Seven data points had numbers of gaps seen higher than 40, with four points associated with the 15-mph speed and three points with the 25-mph speed. Surprisingly, the vehicle speed did not have a higher impact on the number of gaps, although the highest number of gaps seen was indeed related to the 25-mph speed (this scenario had the two aforementioned outliers). On the other hand, Scenario 3 had a long constant 5-s gap between vehicles, which was assumed to be the easiest of the three crossing scenarios. The lowest numbers of gaps seen were easily associated with this scenario as expected. All trials, except for one point with 11 gaps, had values of 5 gaps seen or less. Scenario 1 showed vehicles randomly generated with a variable gap between 2 and 5 s. The random assignment of the vehicle gap should add an uncertainty effect to the analysis made by the subject of the traffic stream. All trials, except for two points, exhibited gaps-seen values of less than 15 in this scenario. Although this scenario was construed initially as having an intermediate crossing difficulty (between Scenarios 2 and 3), the results show the behavior in the gaps seen was quite similar to the “easy-crossing” Scenario 3.

Figure 11 shows bar charts of the same data of gaps seen, but this time is divided by gender and age groups in the sample. The differences in the gaps seen between the groups now become much clearer. When comparing the results across scenarios of the same configuration, the aforementioned trend is confirmed. Scenario 2 has the highest number of gaps seen, but the effect is much more intense in the 66-85 age group. Interestingly enough, the effects of the vehicle speeds and gaps are not similar for the female and male groups. In Configuration 1, females tend to wait for more gaps as age increases, whereas the males tend to reduce their number of gaps seen except for the last 66-85 age group, which substantially increased the number of gaps seen (even after taking the two outlier data points).

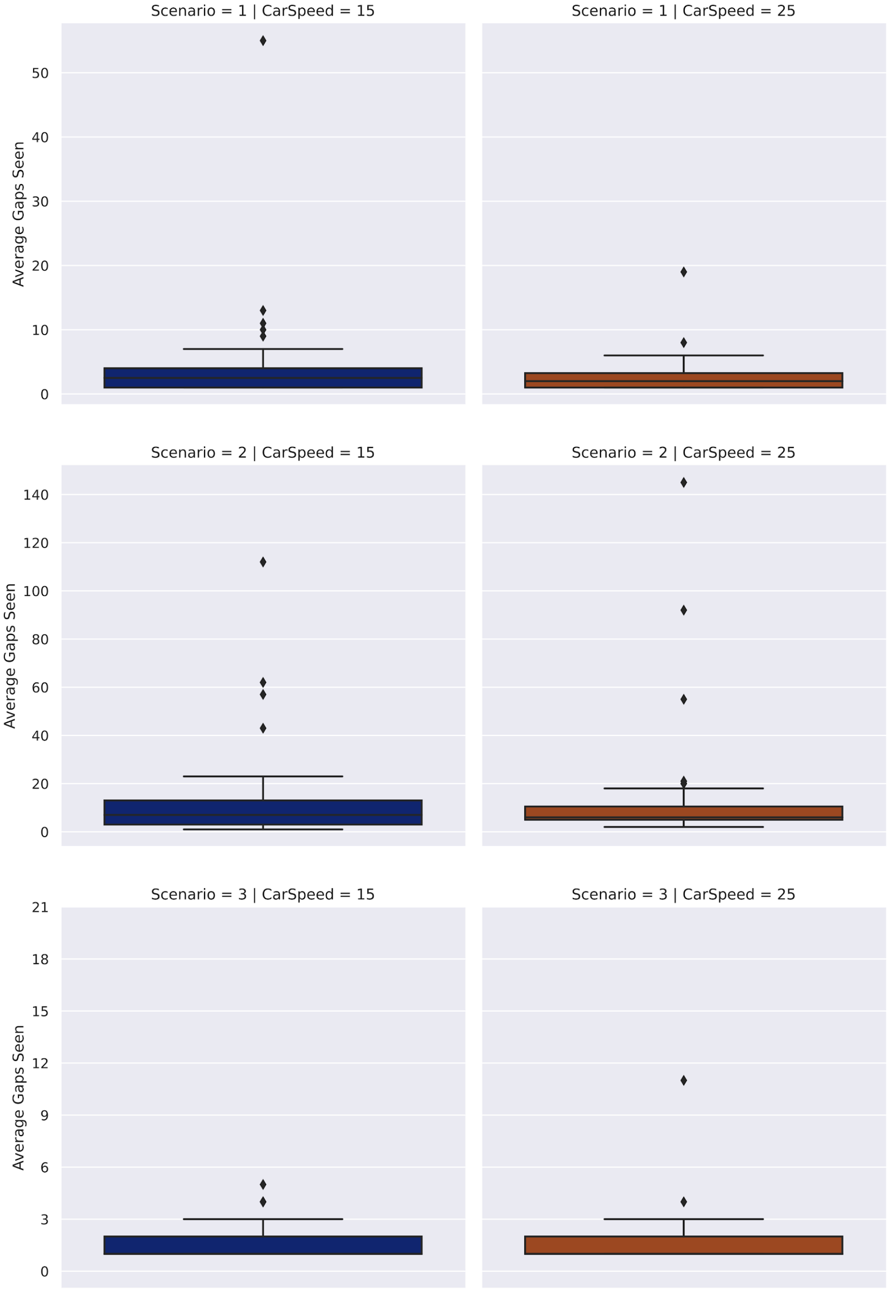

Figure 10 - Box Plots of the Gaps Seen by Scenario and Car Speed Configuration for One-lane Crossing

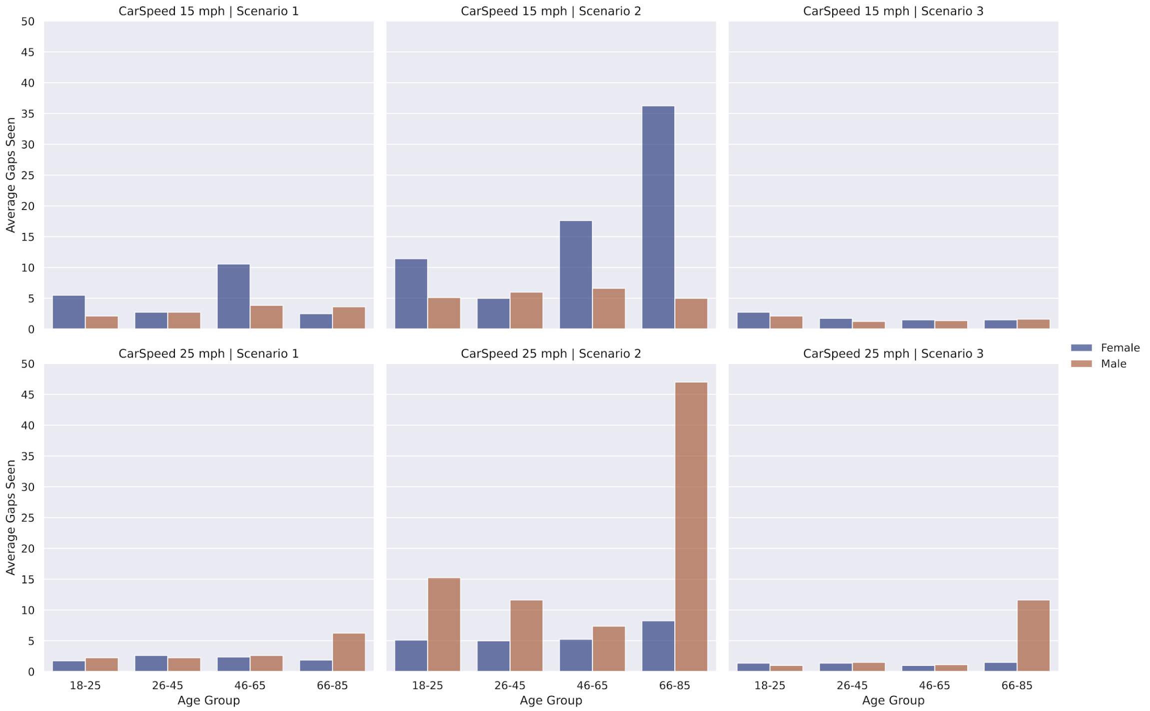

Figure 11 - Average Gaps Seen by Gender vs Age Groups for One-lane Crossing

For Scenario 3, the male 66-85 age group in Configuration 2 was the only subject group that exhibited an average value of gaps seen over 10. All other subject groups, from both configurations, had average values of 3 gaps seen or lower. Therefore, neither the speed of vehicles nor the gender of the subjects seem to affect the high safety perception of the crossing maneuver based on the 5-s gaps. Almost all the groups, except for the aforementioned older males, crossed the road almost immediately after one or two vehicles passed the crossing location.

For the scenario with random gaps, the male 66-85 group is again showing the highest number of gaps seen for Configuration 2. This could represent that this group was composed of risk-averse individuals as the trend observed is confirmed with the other two scenarios. For Configuration 1, two of the female groups exhibited the highest numbers of gaps seen. Another interesting finding is that no apparent trend is present as the two groups were the 18-25 and 46-65 age groups. The female 66-85 group had the lowest average value of gaps seen for the scenario in this configuration.

Table 8 presents the results of the average gap taken (in seconds) and the total quantity of gaps not taken per gap value for each subject in the sample. These results are for Scenario 1, which is the only one with variable gaps between vehicles in the VR experiment. This analysis looks to identify differences in the decision to cross between subject groups. For Configuration 1, male subjects had an average gap taken of 4.49 s with a standard deviation of 0.18 s, whereas female subjects had a higher average gap taken of 4.80 s and a similar standard deviation of 0.19 s. In similar fashion, female subjects had an average number of gaps not taken of 16.13, more than double the average value of 8 gaps not taken by their counterpart male subjects. These results are indicative of female subjects being more conservative when making the decision to cross than the male subjects in the low speed configuration.

When analyzing the results from Configuration 2, the observed trend for the gender groups based on the higher vehicle speed is contradictory. Male subjects had an average gap taken of 4.69 s with a standard deviation of 0.21 s, slightly higher than for the previous configuration. The surprising result is that female subjects had a lower average value of gaps taken of 4.38 s with a higher standard deviation of 0.31 s. The female subjects had a much lower average gap, being more aggressive than their male counterparts. In similar fashion, female subjects had an average number of gaps not taken of 4.63, whereas male subjects had 9.38 gaps not taken.

Table 8 - Average Gaps Taken and Gaps Not Taken per Subject for One-lane Crossing

Vehicle Speed	Gender	ID	Age	Ave. Gap Taken (s)	Number of Gaps Not Taken						
					at 2.0s	at 2.5s	at 3.0s	at 3.5s	at 4.0s	at 4.5s	at 5.0s
15	M	A1	18-25	4.38	1	1	1	1	0	0	0
		A2	18-25	4.25	0	2	0	1	0	2	0
		A3	26-45	4.50	0	0	1	1	0	1	0
		A4	26-45	4.63	2	0	2	2	1	1	3
		A5	46-65	4.67	1	2	2	2	1	0	2
		A6	46-65	4.63	3	2	0	2	2	1	0
		A7	66-85	4.25	0	1	1	0	0	0	0
		A8	66-85	4.63	2	4	4	2	1	2	4
	F	A9	18-25	4.88	0	2	3	3	1	2	2
		A10	18-25	4.88	1	3	4	4	4	3	4
		A11	26-45	4.50	0	0	1	1	0	0	0
		A12	26-45	4.63	0	2	2	2	3	0	3
		A13	46-65	5.00	1	8	7	9	8	10	13
		A14	46-65	5.00	0	2	2	2	1	2	2
		A15	66-85	4.88	0	1	2	2	1	1	0
		A16	66-85	4.63	0	2	0	1	1	1	0
25	M	B1	18-25	4.88	1	2	0	1	1	0	0
		B2	18-25	4.63	1	0	1	2	1	0	0
		B3	26-45	4.88	1	0	0	1	0	1	0
		B4	26-45	4.75	0	2	1	0	3	0	1
		B5	46-65	4.38	2	2	2	2	0	0	0
		B6	46-65	4.38	1	1	1	1	1	0	0
		B7	66-85	4.75	4	4	3	3	2	1	1
		B8	66-85	4.88	3	5	4	4	3	3	2
	F	B9	18-25	3.88	0	1	0	0	0	0	0
		B10	18-25	4.13	1	2	1	0	1	0	0
		B11	26-45	4.50	2	2	3	4	1	0	1
		B12	26-45	4.63	0	0	0	0	0	0	0
		B13	46-65	4.13	0	2	1	1	0	0	0
		B14	46-65	4.38	2	1	2	1	0	1	0
		B15	66-85	4.63	0	0	2	0	0	0	0
		B16	66-85	4.75	0	1	1	2	0	1	0

4.2 Walking Speeds Analysis of One-lane Crossing Scenarios

The walking speed of the subjects was calculated in Unity using their actual position when crossing the road in the VR scenario. The distance traveled by the subject between the two sidewalks was divided by the time that each subject took when exiting the first sidewalk and reaching the second sidewalk on the other side of the road. Figure 12 shows the frequency histogram of the average speed, in ft/s, calculated for each subject when crossing the road. It can be observed that a considerable accumulation of subjects is found having walking speeds between 3 ft/s and 5 ft/s. A small group of subjects shows speeds greater than 6 ft/s, resulting in a skewed distribution to the right. These results confirm that the walking speeds calculated from the VR experiment provide reasonable values and are comparable with values found in the literature.

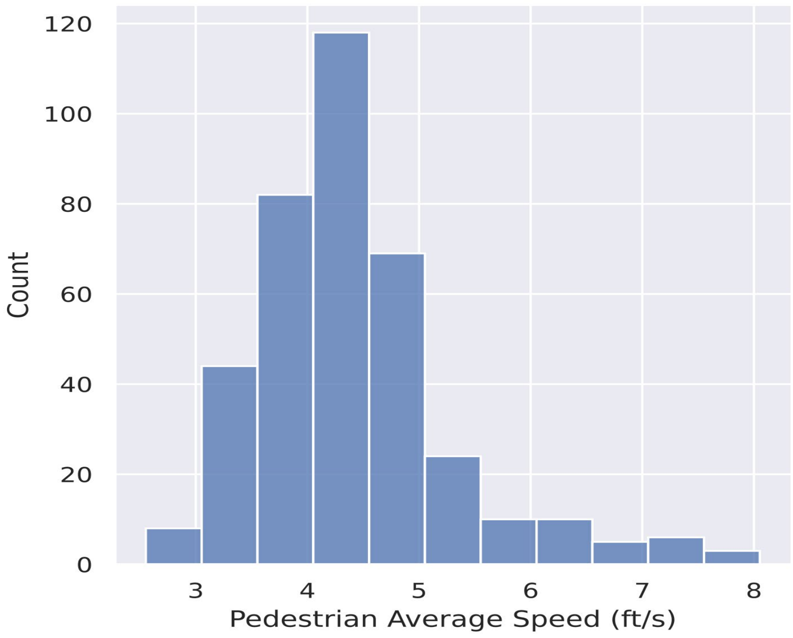

Figure 12 - Average Walking Speeds for One-lane Crossing

A normality check of the walking speed values was made. Figure 13 shows the probability plot of the walking speeds and the theoretical normal distribution for comparison. It is clear from the plot that the walking speeds do not tend to follow the straight line; therefore, normality cannot be assumed for the data.

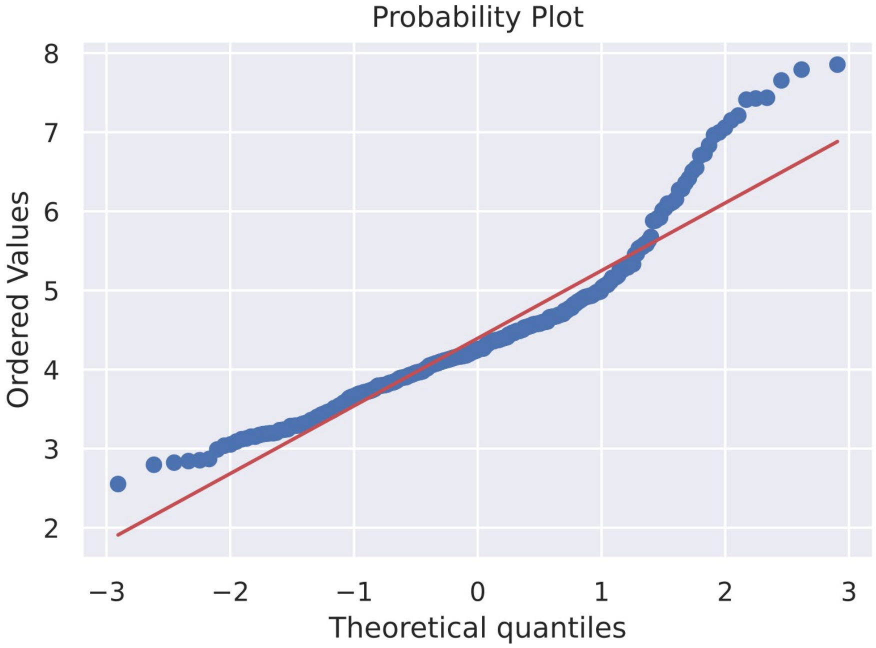

Figure 13 Q-Q Plot of Walking Speeds for One-lane Crossing

Table 9 presents a statistical summary of the average walking speeds per gender and scenario. When comparing each scenario separately, there are no obvious differences in the average walking speeds of the gender groups. The variability of walking speeds is slightly larger for the group of female subjects. When comparing scenarios, Scenario 2, with the shorter 3-s gaps, shows the higher walking speeds for both gender groups, as expected. The effect of the size of the gap between vehicles is noted, as Scenario 3 with the 5-s vehicle gaps had the smaller average walking speeds for both gender groups.

The distribution of the walking speed per gender was analyzed further. Figure 14 shows the histograms of the average walking speeds (ft/s) from all trials by gender. A larger count of female subjects (higher than 70) had a 4 ft/s walking speed, whereas a larger count of male subjects (around 150 subjects) had a range of 3.5 to 5 ft/s. It can be inferred that a group of females has a higher speed when crossing the road to prevent a collision with the moving vehicles, unlike male subjects, of which the majority are in a range between 3 ft/s and 5 ft/s.

Table 9 - Descriptive Statistics of the Walking Speeds for One-lane Crossing

Gender	Scenario	Count	Average Speed (ft/s)	Standard Deviation (ft/s)	Minimum Speed (ft/s)	Maximum Speed (ft/s)
Female	1	63	4.30	1.02	2.84	7.44
	2	63	4.63	1.15	3.18	7.85
	3	64	4.17	0.92	2.55	7.21
Male	1	62	4.36	0.77	3.13	7.15
	2	64	4.75	0.65	3.64	6.71
	3	63	4.17	0.58	3.05	5.33

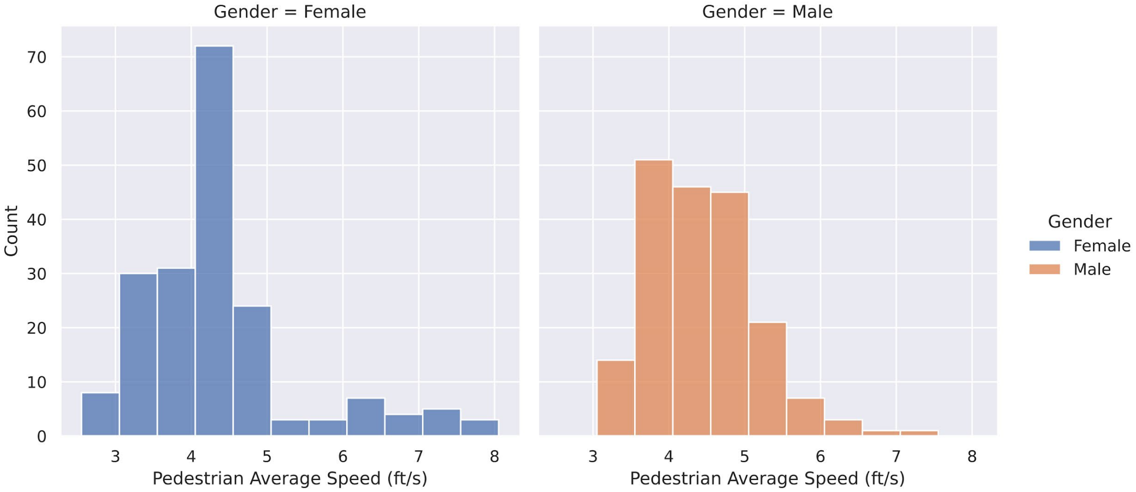

Figure 14 - Pedestrian Walking Speeds per Gender for One-lane Crossing

Normality was again checked for the walking speeds, but now for each gender group separately. Figures 15 and 16 show the probability plots for the male and female groups, respectively. Differences were visually detected regarding the data's normality between males and females. Figure 13 already showed that the total data of walking speeds did not follow a normal distribution. These two probability plots help to observe that the female group has a larger deviation from normality than the male group. A Wilcoxon test of the data was performed with a statistic of 9.054 and a p-value of 0.98. It turned out that there are no significant differences between the male and female distributions at a 95% confidence level.

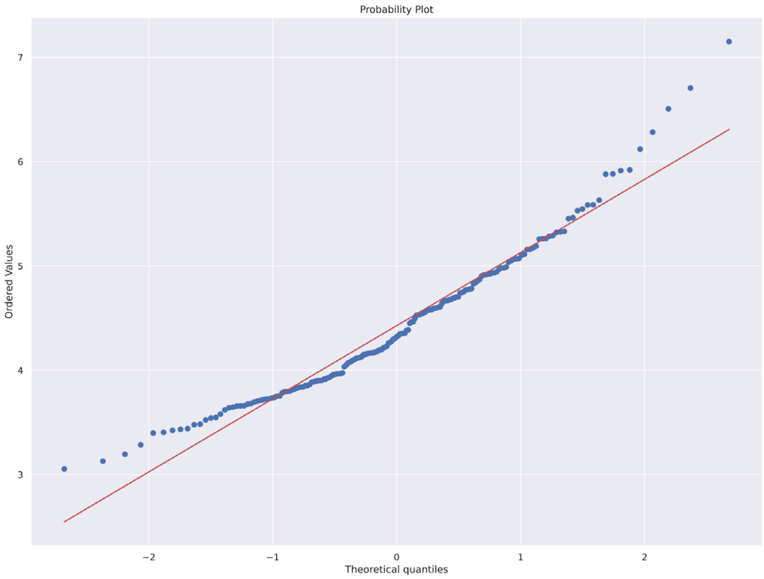

Figure 15 – Q-Q Plot of Walking Speeds for Males in One-lane Crossing

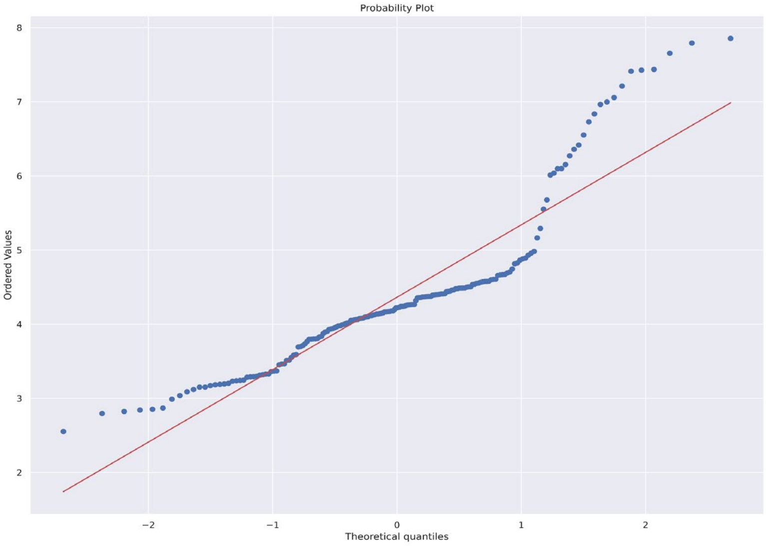

Figure 16 – Q-Q Plot of Walking Speeds for Females in One-lane Crossing

Figure 17 shows the walking speeds grouped by configuration and by gender. This plot shows that the higher walking speeds observed for the distribution of the female group predominantly come from the 25-mph configuration. This configuration indicates that female subjects have a large range of walking speeds between 2.5 ft/s and 8.5 ft/s, with respect to the other distributions where a more significant agglomeration of subjects is observed.

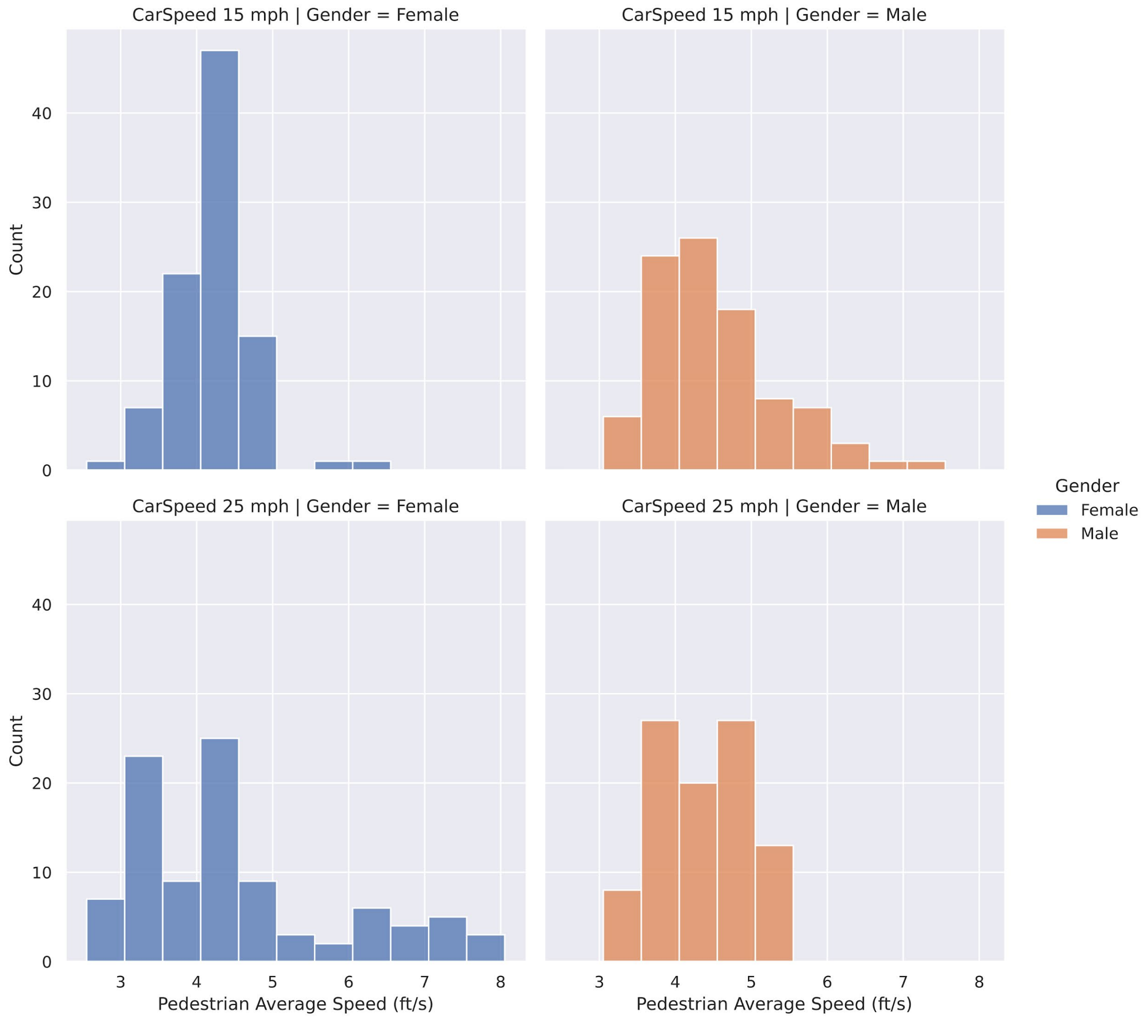

Figure 17 - Walking Speeds per Configuration and Gender in the One-Lane Crossing

Figure 18 shows the histograms of the walking speeds by configuration and age group. These distributions show that the highest walking speeds (and larger range of speeds) belong to the 46-65 age group in Configuration 2. Another age group with high walking speeds and large speed range was the 18-25 age group, but at the 15-mph speed configuration. In contrast, the age group with the smallest range of walking speeds was the 66-85 age group in Configuration 1; all values were inside the 3-5 ft/s range.

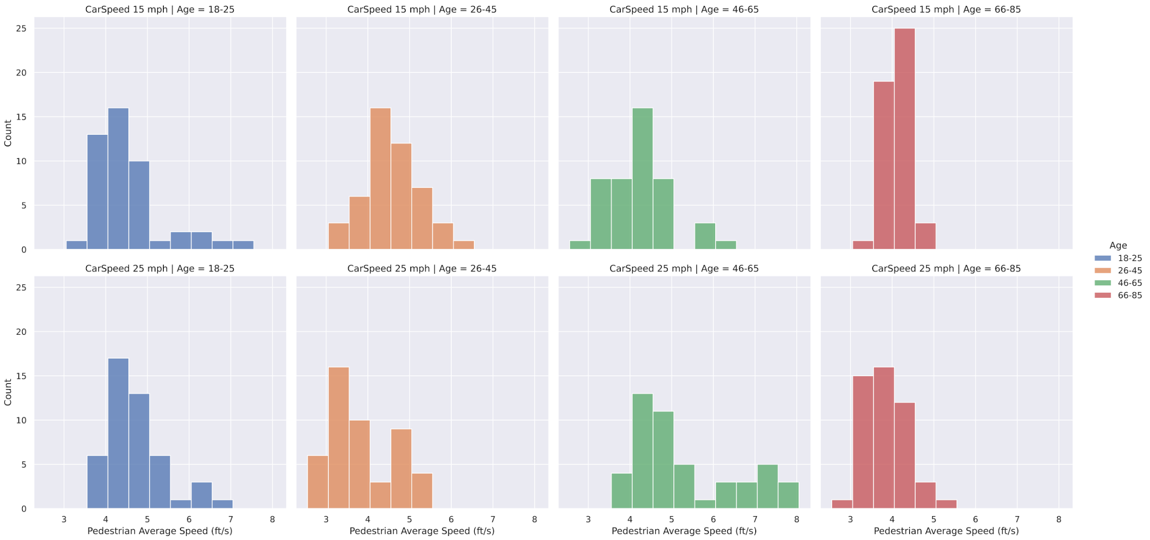

Figure 18 - Walking Speeds by Age Group in the One-Lane Crossing

4.3 Gap Acceptance Analysis of Two-lane Crossing Scenarios

A third group of 16 subjects observed the VR scenarios for the two-lane roadway crossing setting. This configuration only included two scenarios with variable gaps between vehicles (this was Scenario 1 for the one-lane crossing setting). The scenarios with constant gap values were not shown in this configuration. The objective of this configuration was to analyze the changes in pedestrian behavior (i.e., gap acceptance and walking speeds) when crossing the additional lane. The same vehicle speeds of 15 mph and 25 mph were used to create the two scenarios. Different than for the one-lane roadway crossing, now the same subjects saw the two vehicle speeds in the trials. The gap between vehicles was also generated randomly in 0.5-s increments, but now the range was extended from 2 s to a maximum gap value of 8 s.

The experiment was designed for the collection of 10 trials (repetitions) per subject for each demographic group. Each demographic group was composed of two subjects. Two trials of Scenario 2 were noted missing during the processing and analysis of the data. Therefore, a total of 158 observations were obtained for the two-lane road crossing setting.

Table 10 - Descriptive Statistics for the Number of Gaps Seen in the Two-lane Crossing

Vehicle Speed (mph)	Gender	Age	Trials	Average Gaps Seen	Standard Deviation	Minimum Value	Maximum Value
15	Female	18-25	10	2.0	1.15	1	4
		26-45	10	1.3	0.48	1	2
		46-65	10	1.0	0.00	1	1
		66-85	10	2.1	0.88	1	4
	Male	18-25	10	1.1	0.32	1	2
		26-45	10	1.8	0.92	1	3
		46-65	10	1.7	0.95	1	4
		66-85	10	**8.5**	**10.76**	1	29
25	Female	18-25	10	**2.4**	**1.51**	1	6
		26-45	10	2.0	0.67	1	3
		46-65	10	1.6	0.70	1	3
		66-85	10	1.8	**1.03**	1	4
	Male	18-25	8	1.6	0.52	1	2
		26-45	10	1.6	0.70	1	3
		46-65	10	1.8	0.92	1	3
		66-85	10	**15.8**	**20.59**	1	66

Note: Cells in bold show higher values than for the one-lane crossing setting.

Interestingly, all but three of the subject groups in Table 10 had lower average numbers of gaps seen in the two-lane crossing than in the one-lane crossing. The three subject groups with higher average values of gaps and standard deviation seen in the two-lane crossing (cells shown in bold in Table 12) were the two male 66-85 age groups and the female 18-25 age group in the 15-mph speed scenario. That the males from the oldest age group observed more gaps for the two-lane crossing than for the one-lane crossing roadway is not entirely surprising, but not finding a similar trend for the behavior of the female group (and by a very large difference!) is indeed very surprising.

Figure 19 shows the box-plots of the average gaps seen grouped by vehicle speeds. The data from all subjects per scenario was shown aggregated in this figure. As expected, the highest number of gaps seen was found in Scenario 2 with the higher vehicle speeds.

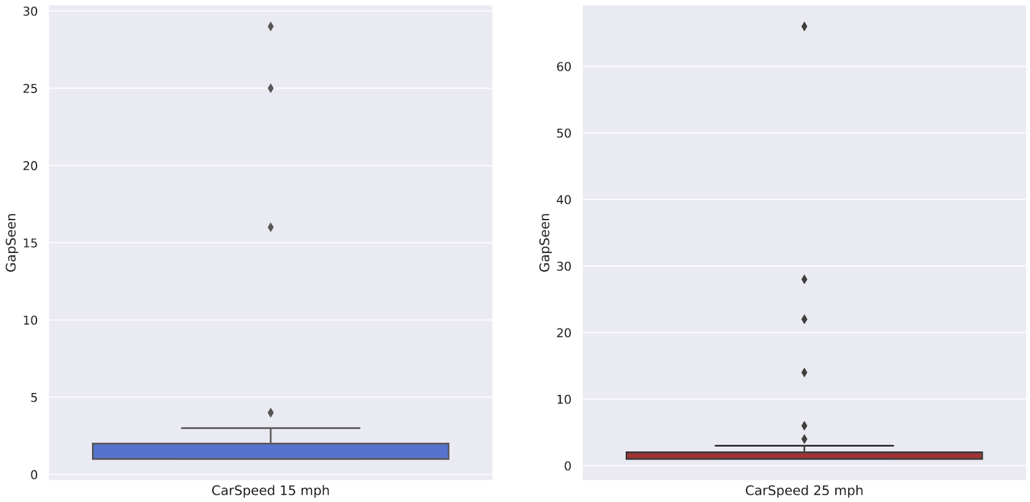

Figure 19 - Box Plots of the Gaps Seen by Vehicle Speed for the Two-lane Crossing

Figure 20 shows bar charts of the same data of gaps seen by the four age groups for each of the two scenarios. In a general sense, the scenario with the 25-mph vehicle speed showed a higher average of gaps seen by the subjects than in the 15-mph vehicle speed scenario. This difference is clearly observed for the two male 66-85 age groups with average values of about 8 gaps and 16 gaps for the 15-and 25-mph speed values, respectively. It can be inferred that pedestrians rejected more gaps at a vehicle speed of 25 mph since the perception of the gap is less, even though the gap range is larger.

Table 11 presents the results of the average gap taken (in seconds) and the total quantity of gaps not taken per gap value for each subject in the sample. This analysis looks to identify differences in the decision to cross between subject groups and the one-lane vs. two-lane crossings. It turned out that the male population of 66-85 years, when faced with vehicles at 25 mph in the two-lane crossing, had the highest average with 15.8 gaps seen, while the averages for the other age groups are from 1 to 8.5 at most.

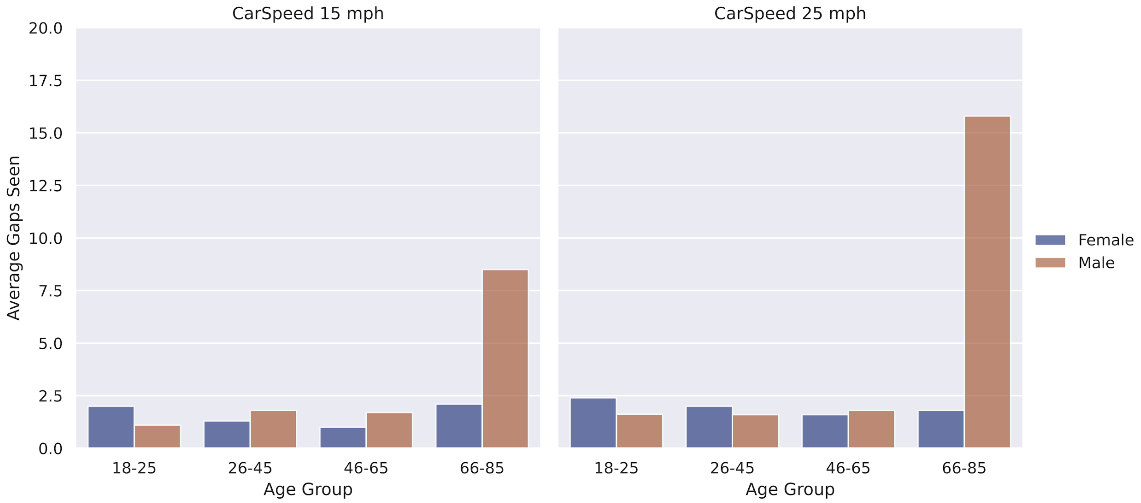

Figure 20 - Average Gaps Seen by Gender Group and Vehicle Speeds in the Two-lane Crossing

In terms of the differences in gaps taken between the 15-mph and 25-mph vehicle speeds, both female and male groups have lower averages in the low-speed setting. The male group had an average gap taken of 6.95 s with a standard deviation of 0.52 s in the 15-mph scenario, whereas the average gap taken was reduced to 6.64 s with a standard deviation of 0.59 s in the 25-mph scenario. A similar trend was observed for the female groups; they had an average gap taken of 6.69 s with a standard deviation of 0.61 s in the 15-mph scenario, whereas the average gap taken was reduced to 6.40 s with a standard deviation of 0.79 s in the 25-mph scenario. The decreasing trend in average value for the female group was similar as in the one-lane crossing setting. When analyzing the number of gaps not taken by the subjects, the males had higher numbers of gaps not taken than the females for both speed scenarios. Male subjects took an average of 11.38 gaps in the 15-mph scenario and 20.88 gaps in the 25-mph scenario before crossing the two-lane road. Female subjects took an average of 3 gaps in the 15-mph scenario and 4.75 gaps in the 25-mph scenario.

Table 11 - Average Gaps Taken and Gaps Not Taken per Subject for the Two-lane Crossing

Vehicle Speed	Gender	ID	Age	Ave. Gap Taken (s)	Number of Gaps Not Taken												
					At 2.0s	At 2.5s	At 3.0s	At 3.5s	At 4.0s	At 4.5s	At 5.0s	At 5.5s	At 6.0s	At 6.5s	At 7.0s	At 7.5s	At 8.0s
15	M	C1	18-25	7.20	0	0	0	0	0	0	0	0	0	0	0	0	0
		C2	18-25	6.90	0	0	0	0	0	1	0	0	0	0	0	0	0
		C3	26-45	6.90	0	0	0	1	2	0	0	0	0	0	0	0	0
		C4	26-45	6.60	0	0	0	2	1	2	0	0	0	0	0	0	0
		C5	46-65	7.50	0	0	0	1	0	1	1	0	0	2	0	0	0
		C6	46-65	7.20	0	0	0	1	0	0	0	1	0	0	0	0	0
		C7	66-85	5.90	0	0	0	0	2	0	0	0	0	0	0	0	0
		C8	66-85	7.40	0	0	7	8	7	6	7	7	7	5	6	6	7
	F	C9	18-25	7.60	0	0	1	0	1	3	0	1	1	2	0	0	0
		C10	18-25	6.10	0	0	0	0	1	0	0	0	0	0	0	0	0
		C11	26-45	5.90	0	0	0	0	0	0	1	0	0	0	0	0	0
		C12	26-45	6.30	0	0	0	1	0	0	1	0	0	0	0	0	0
		C13	46-65	7.20	0	0	0	0	0	0	0	0	0	0	0	0	0
		C14	46-65	7.00	0	0	0	0	0	0	0	0	0	0	0	0	0
		C15	66-85	7.10	0	0	0	2	0	1	1	0	0	0	0	0	0
		C16	66-85	6.30	0	0	0	0	2	1	2	0	1	0	1	0	0
25	M	C1	18-25	6.40	0	0	1	1	0	1	0	0	0	0	0	0	0
		C2	18-25	6.50	0	0	1	1	0	0	0	0	0	0	0	0	0
		C3	26-45	7.00	0	0	0	2	0	0	1	0	0	0	0	0	0
		C4	26-45	6.90	0	0	0	1	0	0	2	0	0	0	0	0	0
		C5	46-65	6.10	0	0	1	2	0	1	0	1	1	0	2	0	0
		C6	46-65	6.90	0	0	0	0	0	0	0	0	0	0	0	0	0
		C7	66-85	5.70	0	0	0	0	1	0	0	0	0	0	0	0	0
		C8	66-85	7.60	0	0	14	13	14	14	14	14	13	13	14	12	12
	F	C9	18-25	7.00	0	0	1	1	2	0	2	2	0	1	1	2	0
		C10	18-25	6.10	0	0	1	1	0	0	0	0	0	0	0	0	0
		C11	26-45	6.80	0	0	1	1	1	1	1	0	0	1	0	0	0
		C12	26-45	5.80	0	0	0	1	1	1	1	0	0	0	0	0	0
		C13	46-65	6.50	0	0	1	1	0	0	0	0	0	0	0	0	0
		C14	46-65	4.90	0	0	2	0	0	1	0	0	0	1	0	0	0
		C15	66-85	6.70	0	0	1	0	0	0	0	1	0	0	0	0	0
		C16	66-85	7.40	0	0	2	1	0	1	0	0	1	0	1	0	0

4.4 Walking Speeds Analysis of Two-lane Crossing Scenarios

Figure 21 shows the frequency histogram of the walking speed, in ft/s, calculated for each subject when crossing the two-lane road. It can be observed that most of the subjects have walking speeds between 3 ft/s and 5 ft/s. Similar to the case of the one-lane crossing, a small group of subjects show speeds greater than 6 ft/s, resulting in a skewed distribution to the right. Again, the results obtained for the two-lane crossing that were calculated from the VR experiment provide reasonable values that are comparable with values found in the literature.

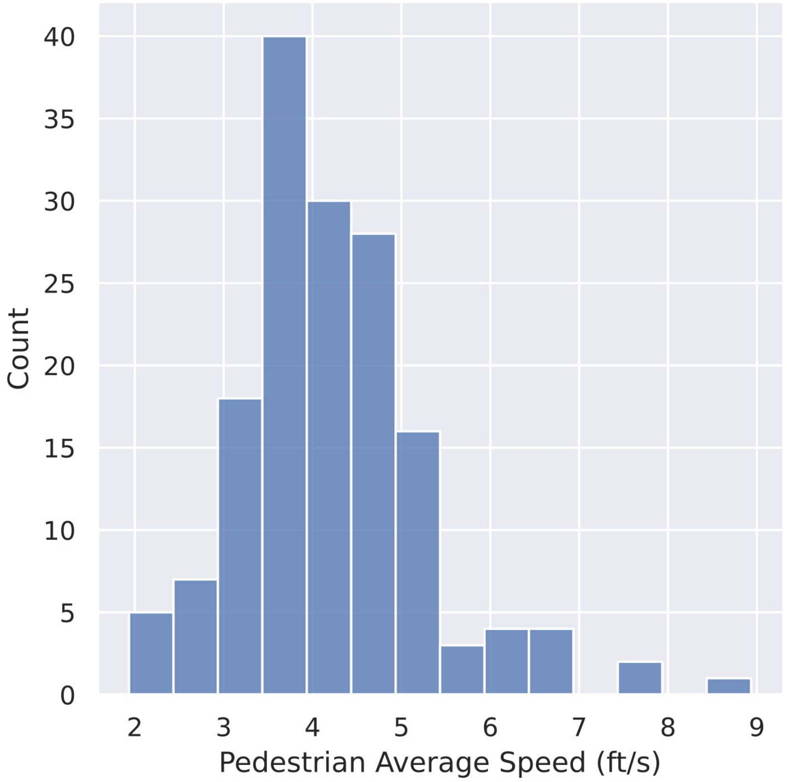

Figure 21 - Pedestrian Average Speed Frequency for Two-lane Crossing

A normality check of the walking speed values was made. Figure 22 shows the probability plot of the walking speeds and the theoretical normal distribution for comparison. It is clear from the plot that the walking speeds do not tend to follow the straight line, so normality cannot be assumed for the data. It is observed that atypical speed data more significant than 5.5 ft/s do not allow normality.

Table 12 presents a statistical summary of the average walking speeds per gender and scenario. As in the one-lane crossing, when comparing each scenario separately, there are no obvious differences in the average walking speeds between the two gender groups. Similar to the case of the one-lane crossing, the variability of walking speeds is slightly larger for the group of female subjects. It is interesting to note that the trend of walking speed is opposite between males and females; females tend to walk slightly faster in the 25-mph scenario and males tend to walk slightly slower in the 25-mph scenario.

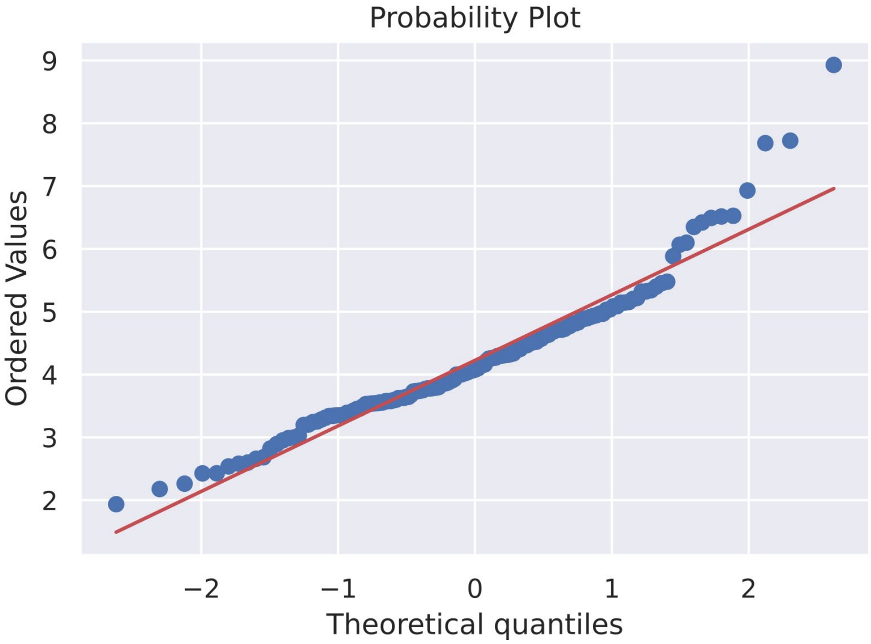

Figure 22 - Q-Q Plot of Walking Speeds for Two-lane Crossing

Table 12 - Descriptive Statistics of Walking Speed for Two-lane Crossing

Gender	Vehicle Speed (mph)	Trials	Average Walking Speed (ft/s)	Standard Deviation (ft/s)	Minimum Speed (ft/s)	Maximum Speed (ft/s)
Female	15	40	4.19	1.04	2.60	6.93
	25	40	4.26	1.39	2.26	8.93
Male	15	40	4.34	0.99	2.18	6.49
	25	38	4.11	0.78	1.93	5.32

The distribution of the walking speed per gender was again analyzed per subject group. Figure 23 shows the histograms of the walking speeds (ft/s) from all trials by gender. Similar to the trend observed in the one-lane crossing setting, there is a group of females that exhibited walking speeds higher than 7 ft/s, although at a smaller scale.

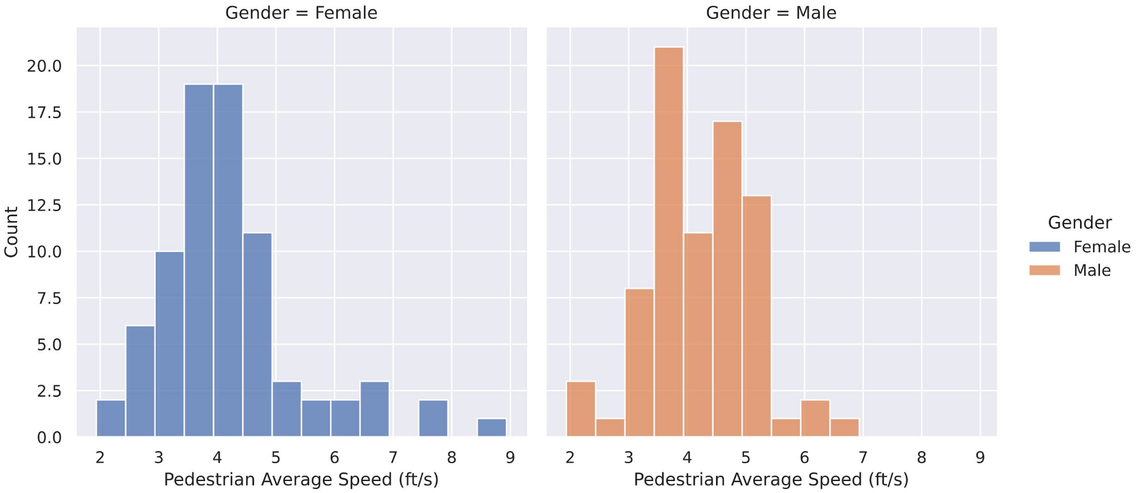

Figure 23 - Pedestrian Average Speed Frequency by Gender for Two-lane Crossing

Normality was again checked for the walking speeds, but now for each gender group separately. Figures 24 and 25 show the probability plots for the male and female groups, respectively. Differences were again visually detected regarding the data's normality between males and females. These two probability plots help to observe that the female group might have a larger deviation from normality than the male group. A Wilcoxon test was performed with a statistic of 1.294 and a p-value of 0.22. It turned out that there are no significant differences between the male and female distributions at a 95% confidence level, as was the case for the one-lane roadway crossing.

Figure 26 shows the extreme walking speed values observed for the female group distribution. Also, it is noted that the vast majority of the values in the two samples accumulate at a walking speed of approximately 4.5 ft/s.

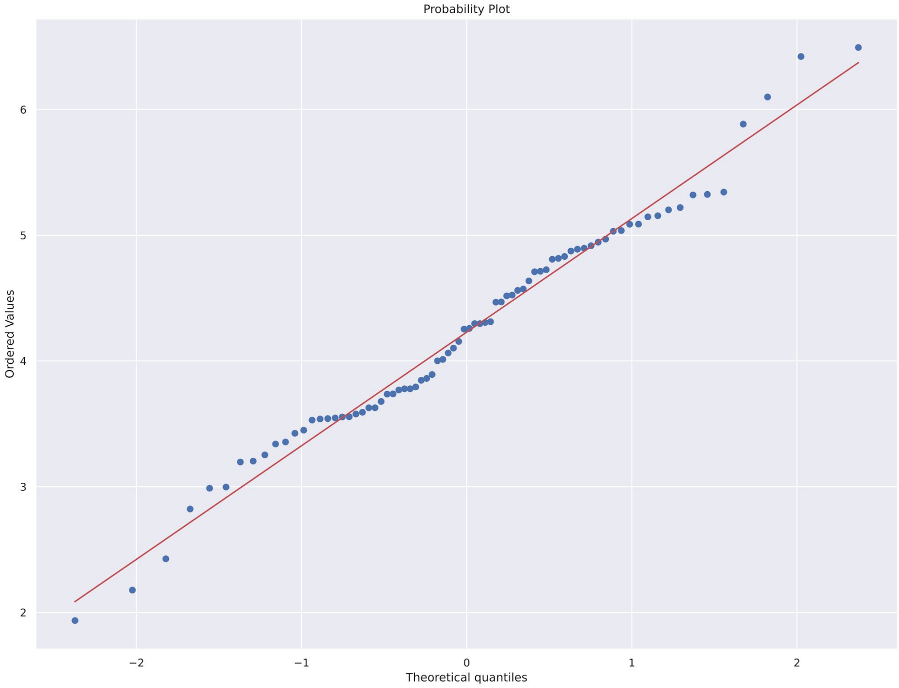

Figure 24 - Q-Q Plot of Walking Speeds for Males in the Two-lane Crossing

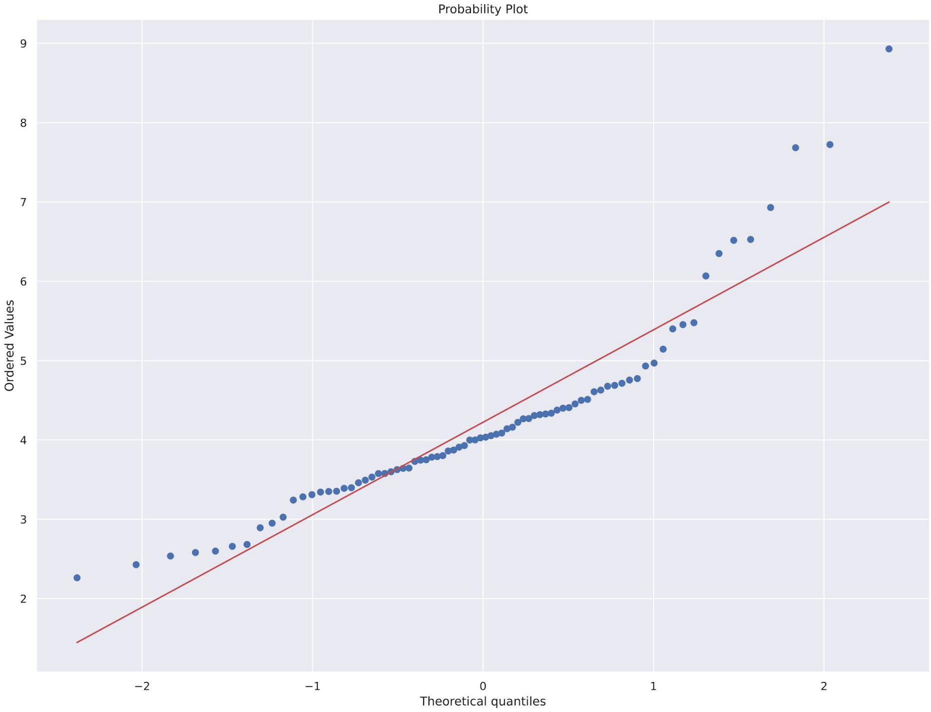

Figure 25 - Q-Q Plot of Walking Speeds for Females in the Two-lane Crossing

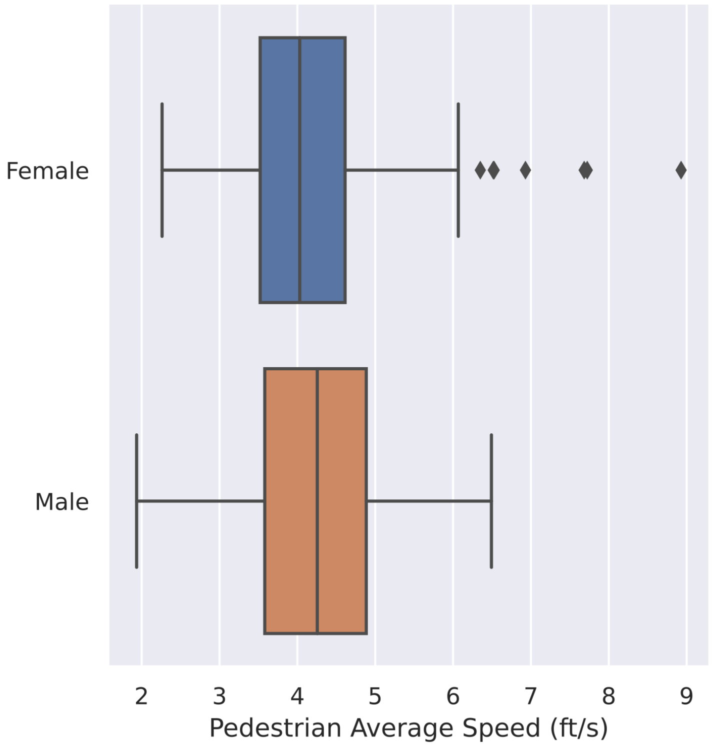

Figure 26 - Box Plots of the Walking Speed by Gender for the Two-lane Crossing

Figure 27 shows the walking speeds grouped by scenario (speed of the vehicles) and by gender. The distribution for females in the 25-mph scenario shows there is a high dispersion in a range of speeds between 2 ft/s and 8.5 ft/s, with respect to the other graphs where a more significant agglomeration of subjects is observed. Also, it is noted that the male group in the 25-mph scenario does not exhibit walking speeds higher than 5.5 ft/s, whereas the other three groups exceed that walking speed.

Figure 28 shows the histograms of the walking speeds by speed scenario and age group. Similar to the one-lane crossing, the distributions show that the highest walking speeds (and larger range of speeds) belong to the 46-65 age group in Scenario 2. Another age group with high walking speeds and large speed range was the 18- to 25-year-old group, but at the 15-mph speed. In contrast, the age group with the smallest range of walking speeds was the 18-25 age group in Scenario 1, which had all values inside the 3-5.5 ft/s range.

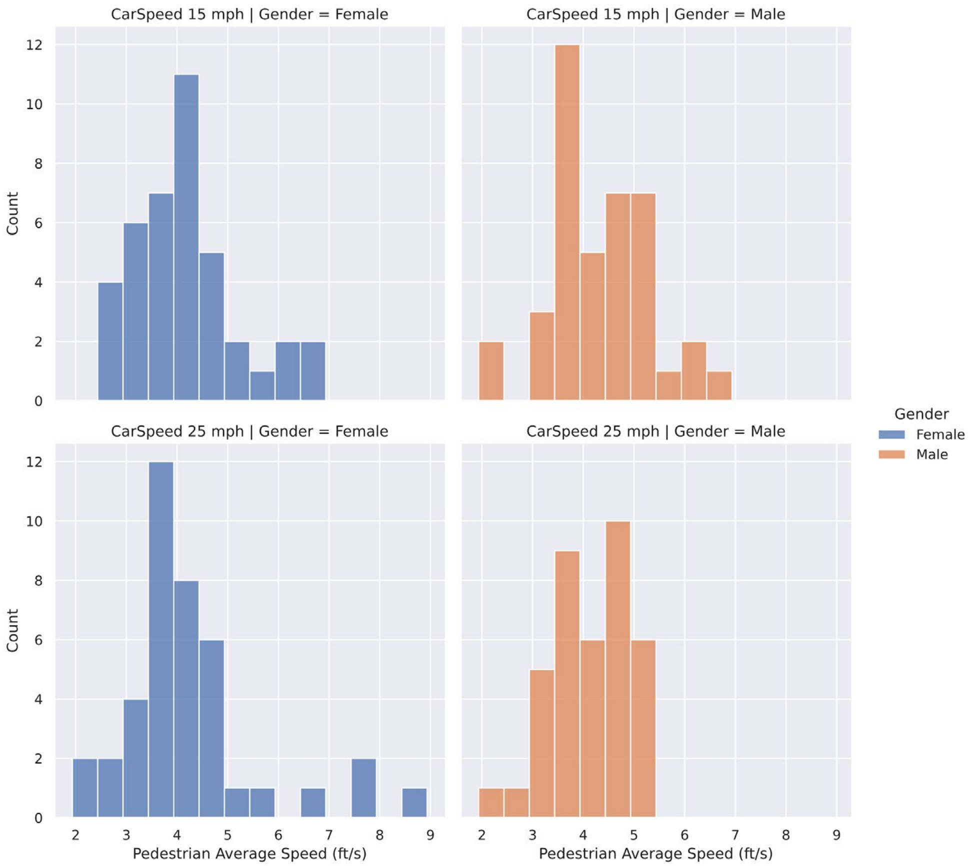

Figure 27 - Walking Speeds per Scenario and Gender in the Two-lane Crossing

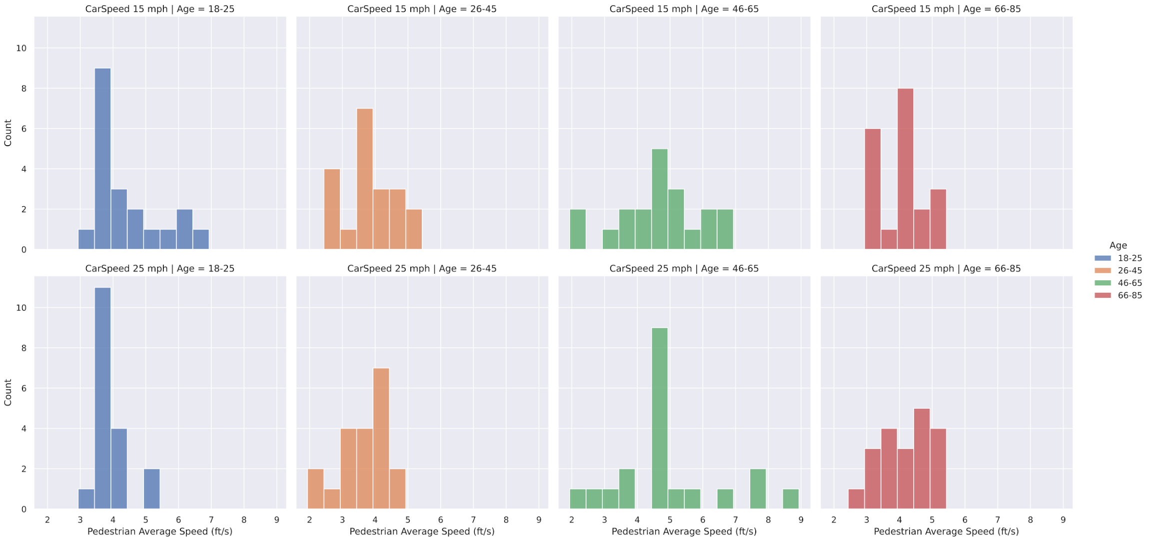

Figure 28 - Walking Speeds per Scenario and Age in the Two-lane Crossing

4.5 Crossing Success Rate Analysis

The crossing success rate was calculated for each subject in the VR experiment to identify if any of the subject groups had any significant issues with hits by a moving vehicle when crossing. Table 13 shows the overall crossing success rates divided by scenario and configuration. Not surprisingly, the combination with the worst crossing success rate of 79.7% was observed for the subject group that participated in the scenario with the 25-mph vehicle speed and short constant gap of 3 s in the one-lane setting. A perfect crossing success rate was observed for the subjects in the two scenarios with the “long” 5-s gaps in the one-lane setting, irrespective of the vehicle speeds.

Table 13 - Crossing Success Rates by Scenario and Vehicle Speed

Scenario	Vehicle Speed (mph)	Crossing Success Rate One-Lane Road	Crossing Success Rate Two-Lane Road
1	15	0.984	1.000
	25	0.984	0.987
2	15	0.984	
	25	0.797	
3	15	1.000	
	25	1.000	

Table 14 shows the crossing success rates by gender group. The results show that in the one-lane road setting, the male group exhibited a better crossing success rate than their female counterparts, 97.4% vs. 94.2%. In the two-lane road setting, the trend is reversed, with females having a perfect success rate and the males having a lower but fairly similar rate of 98.7%.

Table 14 - Crossing Success Rate by Gender

Gender	Crossing Success Rate - One-Lane Road	Crossing Success Rate - Two-Lane Road
Female	0.942	1.000
Male	0.974	0.987

Table 15 shows the crossing success rates by age group. In general, three of the age groups exhibited a better success crossing rate in the two-lane setting than in the one-lane setting, except the 46- to 65-year-old cohort that exhibited a 97.5% success rate in the two-lane setting vs. a perfect rate in the one-lane setting. When comparing age groups in the one-lane setting, the worst crossing success rate was observed for the 66-85 age cohort with 89.5%.

Table 15 - Crossing Success Rate by Age

Age	Crossing Success Rate - One-Lane Road	Crossing Success Rate - Two-Lane Road
18-25	0.989	1.000
26-45	0.948	1.000
46-65	1.000	0.975
66-85	0.896	1.000

4.6 Responses from the Pre-Test and Post-Test Questionnaires

Tables 16 and 17 show the responses obtained for two of the questions from the pre-test questionnaire about their level of confidence when crossing a road outside an intersection and the factors they consider when making the decision to cross, respectively.

Table 16 indicates that 38% of the sample feel somewhat or very doubtful of being able to safely cross a road outside an intersection. On the other hand, 34% of the sample feels confidence in being able to cross safely.

Table 16 - Responses to the Question: ***How confident are you to be able to safely cross a one-lane/two-lane road in a place outside an intersection?***

Responses	Configuration 1	Configuration 2	Configuration 3	Total Responses
Very Confident	3	3	2	8
Somewhat Confident	3	2	2	7
Depends, Neither Confident nor Doubtful	3	5	4	12
Somewhat Doubtful	5	3	5	13
Very Doubtful	0	2	2	4
Total	14	15	15	44

Table 17 presents the responses provided toward the factors the subjects consider when making the decision to cross the road. Subjects could select more than one of the factors in the table. The vehicle speed was the factor most selected by the subjects (26% of the sample), followed by the gap between vehicles, the traffic volume, and the road width (19% of the sample), as considered when crossing a road. The time between vehicles was selected by just 15% of the subjects.

Table 17 - Responses to the Question: ***Which of the following factors do you consider when deciding to cross a road outside an Intersection?***

Factors	Configuration 1	Configuration 2	Configuration 3	Total Responses
Vehicle Speeds	13	14	15	42
Available Distance between Vehicles	10	10	11	31
Number of Vehicles	8	13	10	31
Road Width	10	9	12	31
Time between Vehicles	8	9	8	25
Other	0	3	1	4

Tables 18-20 show the responses obtained for the question related to the level of difficulty of crossing the road associated with the variables used in the VR simulation. As expected, the subjects in Configuration 2 (Table 19), with the higher 25-mph vehicle speeds, identified the vehicle speed as a factor more difficult to manage than in Configuration 1 with the lower 15-mph vehicle speed (Table 18). Notwithstanding this result, subjects in Configuration 1 indicated having more difficulty crossing the road in the simulation based on the distance and time between vehicles. The road width that had a fixed value of 10 ft for both Configuration 1 and 2 was not considered as a difficulty factor in crossing the road by any subject in Configurations 1 and 2.

Table 18 – Crossing Difficulty Level for the One-Lane Street in Configuration 1

Factor in VR Simulation	Very Difficult	Somewhat Difficult	Not Difficult
Vehicle Speeds	1	4	9
Distance between Vehicles	0	8	6
Time between Vehicles	0	9	4
Number of Vehicles	0	3	9
Road Width	0	0	14

For Configuration 2, the subjects expressed having more difficulty crossing based on the time observed between vehicles. Distance and time between vehicles were both included in the questionnaire to compare the responses given by the subjects. As observed, in the responses, subjects are more aware of the time variable than the distance variable in the simulations, even though both variables expressed the same information.

Table 19 – Crossing Difficulty Level for the One-Lane Street in Configuration 2

Factor in VR Simulation	Very Difficult	Somewhat Difficult	Not Difficult
Vehicle Speed	1	8	6
Distance between Vehicles	0	7	8
Time between Vehicles	0	10	5
Number of Vehicles	1	5	8
Road Width	0	0	14

Table 20 shows the responses for Configuration 3, the two-lane road setting, and it is observed that there were no factors identified as very difficult. A majority of the subjects indicated that the factors were not complicated, except for the time between vehicles. Similar to the other configurations, the time between vehicles was the factor categorized as "somewhat difficult" by the highest number of subjects.

Table 20 – Crossing Difficulty Level for the Two-Lane Street

Factor in VR Simulation	Very Difficult	Somewhat Difficult	Not Difficult
Vehicle Speed	0	4	9
Distance between Vehicles	0	5	8
Time between Vehicles	0	8	6
Number of Vehicles	0	3	9
Road Width	0	1	12

5. Conclusions and Recommendations

This research study focuses on understanding pedestrian behavior in terms of gap acceptance and walking speeds in urban settings using virtual reality (VR) simulation. The presented methodology allows us to quantify the human behavior of the driver-pedestrian iteration and its response under different scenarios that represent the influence of the urban area. Two vehicle speeds, 15 mph and 25 mph, and three vehicle gap values, 3 s, 5 s, and randomly generated ranges from 2 to 5 s and 2 to 8 s, were used to create eight simulation scenarios. Two roadway configurations, one-lane vs. two-lanes, of an urban street were included.

Based on the research methodology and the scenarios evaluated as part of this study, the following conclusions are made.

1. In terms of pedestrian walking speed, for a one-lane urban scenario, there are two female population groups who had walking speeds greater than 6 ft /s, namely the 18-25 and 46-65 age groups.
2. For the two-lane crossing, the walking speed trend is similar for both age groups and gender as compared to the single-lane scenario variable.
3. Although the speed datasets did not meet the normality test criteria, when discriminated by gender, they showed no significant differences between the distributions. Differences in walking speed were visually observed between the distributions for the age groups.
4. The research methodology using VR technology reasonably predicted the behavior of pedestrians when they were in a controlled environment. The study of the application of innovative safety countermeasures, such as new traffic control devices, can potentially be studied using VR technology as part of the experimental procedures considered for future traffic control devices in the MUTCD.

6. Future Research

Based on the findings of this gap acceptance and walking speed research for both one-lane and two-lane scenarios in an urban setting, it is recommended as future research work to create a robust statistical model to study the nature of pedestrians' behavior when crossing the street. Statistical models will correlate the different response variables obtained from the VR simulation scenarios with the demographic characteristics of the sample and the traffic gaps and speed values for the one-lane and two-lane crossings. Furthermore, this study can be replicated with special interest groups, diverse mobility populations, senior persons, etc., as initially intended for the project.

The situations presented in this report correspond to activities where the ethnic group that controls the experiment were Hispanic/Latino. The research methodology (sampling, training methods) using VR simulation can be adapted to similar urban scenarios and gap acceptance where other cultures or a combination of them prevail (i.e., African American, American Indian, Asian, etc.)

7. Acknowledgments

This material is based upon work supported by the Safety Research Using Simulation (SAFER-SIM) University Transportation Center and funded by the U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology under Grant No.1001814551. Any opinions, findings, or conclusions expressed in this material are those of the authors and do not necessarily reflect the views of the U.S. Department of Transportation. The authors are greatly thankful to the subjects who participated in this study.

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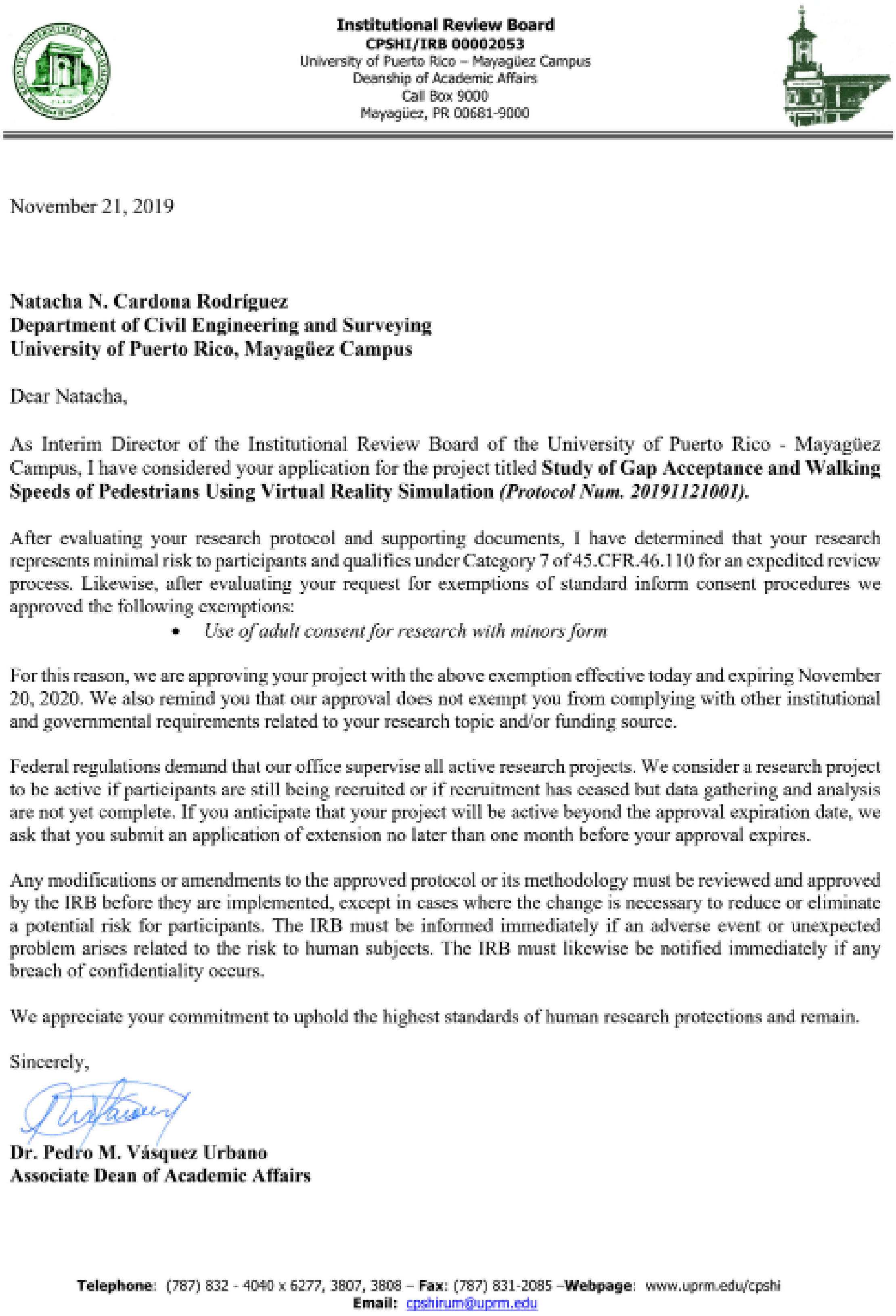
Appendices

Appendix A: UPRM IRB Authorization Letter



Institutional Review Board
CPSHI/IRB 00002053
University of Puerto Rico – Mayagüez Campus
Deanship of Academic Affairs
Call Box 9000
Mayagüez, PR 00681-9000

November 21, 2019

Natacha N. Cardona Rodríguez
Department of Civil Engineering and Surveying
University of Puerto Rico, Mayagüez Campus

Dear Natacha,

As Interim Director of the Institutional Review Board of the University of Puerto Rico - Mayagüez Campus, I have considered your application for the project titled **Study of Gap Acceptance and Walking Speeds of Pedestrians Using Virtual Reality Simulation *(Protocol Num. 20191121001).***

After evaluating your research protocol and supporting documents, I have determined that your research represents minimal risk to participants and qualifies under Category 7 of 45.CFR.46.110 for an expedited review process. Likewise, after evaluating your request for exemptions of standard inform consent procedures we approved the following exemptions:

- *Use of adult consent for research with minors form*

For this reason, we are approving your project with the above exemption effective today and expiring November 20, 2020. We also remind you that our approval does not exempt you from complying with other institutional and governmental requirements related to your research topic and/or funding source.

Federal regulations demand that our office supervise all active research projects. We consider a research project to be active if participants are still being recruited or if recruitment has ceased but data gathering and analysis are not yet complete. If you anticipate that your project will be active beyond the approval expiration date, we ask that you submit an application of extension no later than one month before your approval expires.

Any modifications or amendments to the approved protocol or its methodology must be reviewed and approved by the IRB before they are implemented, except in cases where the change is necessary to reduce or eliminate a potential risk for participants. The IRB must be informed immediately if an adverse event or unexpected problem arises related to the risk to human subjects. The IRB must likewise be notified immediately if any breach of confidentiality occurs.

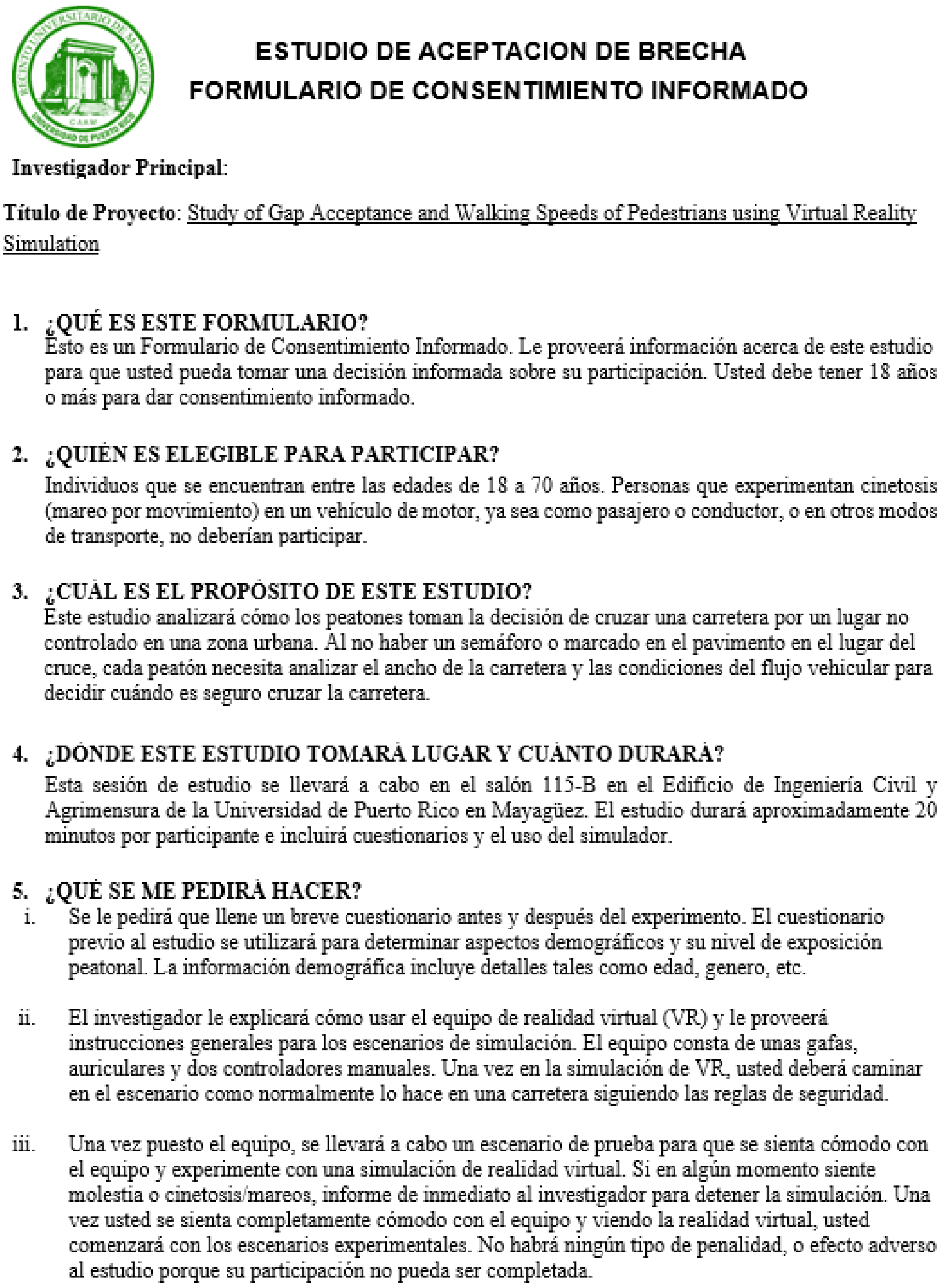
We appreciate your commitment to uphold the highest standards of human research protections and remain.

Sincerely,

Dr. Pedro M. Vásquez Urbano
Associate Dean of Academic Affairs

Telephone: (787) 832 - 4040 x 6277, 3807, 3808 – **Fax**: (787) 831-2085 –**Webpage**: www.uprm.edu/cpshi
Email: cpshirum@uprm.edu

Appendix B: Informed Consent Document



ESTUDIO DE ACEPTACION DE BRECHA
FORMULARIO DE CONSENTIMIENTO INFORMADO

Investigador Principal:

Título de Proyecto: Study of Gap Acceptance and Walking Speeds of Pedestrians using Virtual Reality Simulation

1. **¿QUÉ ES ESTE FORMULARIO?**
   Esto es un Formulario de Consentimiento Informado. Le proveerá información acerca de este estudio para que usted pueda tomar una decisión informada sobre su participación. Usted debe tener 18 años o más para dar consentimiento informado.

2. **¿QUIÉN ES ELEGIBLE PARA PARTICIPAR?**
   Individuos que se encuentran entre las edades de 18 a 70 años. Personas que experimentan cinetosis (mareo por movimiento) en un vehículo de motor, ya sea como pasajero o conductor, o en otros modos de transporte, no deberían participar.

3. **¿CUÁL ES EL PROPÓSITO DE ESTE ESTUDIO?**
   Este estudio analizará cómo los peatones toman la decisión de cruzar una carretera por un lugar no controlado en una zona urbana. Al no haber un semáforo o marcado en el pavimento en el lugar del cruce, cada peatón necesita analizar el ancho de la carretera y las condiciones del flujo vehicular para decidir cuándo es seguro cruzar la carretera.

4. **¿DÓNDE ESTE ESTUDIO TOMARÁ LUGAR Y CUÁNTO DURARÁ?**
   Esta sesión de estudio se llevará a cabo en el salón 115-B en el Edificio de Ingeniería Civil y Agrimensura de la Universidad de Puerto Rico en Mayagüez. El estudio durará aproximadamente 20 minutos por participante e incluirá cuestionarios y el uso del simulador.

5. **¿QUÉ SE ME PEDIRÁ HACER?**
   i. Se le pedirá que llene un breve cuestionario antes y después del experimento. El cuestionario previo al estudio se utilizará para determinar aspectos demográficos y su nivel de exposición peatonal. La información demográfica incluye detalles tales como edad, genero, etc.

   ii. El investigador le explicará cómo usar el equipo de realidad virtual (VR) y le proveerá instrucciones generales para los escenarios de simulación. El equipo consta de unas gafas, auriculares y dos controladores manuales. Una vez en la simulación de VR, usted deberá caminar en el escenario como normalmente lo hace en una carretera siguiendo las reglas de seguridad.

   iii. Una vez puesto el equipo, se llevará a cabo un escenario de prueba para que se sienta cómodo con el equipo y experimente con una simulación de realidad virtual. Si en algún momento siente molestia o cinetosis/mareos, informe de inmediato al investigador para detener la simulación. Una vez usted se sienta completamente cómodo con el equipo y viendo la realidad virtual, usted comenzará con los escenarios experimentales. No habrá ningún tipo de penalidad, o efecto adverso al estudio porque su participación no pueda ser completada.

iv. Después de completar los escenarios, se le proporcionará un cuestionario posterior al experimento para recopilar información sobre su decisión de cruzar o no cruzar la carretera y para obtener recomendaciones para mejorar la experiencia de realidad virtual para futuros estudios de investigación.

6. ¿EXISTE ALGÚN RIESGO O BENEFICIO ASOCIADO CON LA PARTICIPACION?

En términos de la operación del equipo de realidad virtual, existe un leve riesgo de cinetosis (mareos). Un pequeño porcentaje de los participantes podrían experimentar sensación de nauseas o nausea actual. El experimento ha sido trabajado para minimizar el riesgo. Se recomienda que si usted ha experimentado cinetosis (mareos) mientras viaja o maneja un vehículo real, usted no debería participar en este experimento.

Si durante la simulación, usted siente molestia o nauseas, debe informar al investigador inmediatamente para que la simulación pueda ser detenida. La interrupción de la simulación debería de reducir la molestia rápidamente. Si usted no se siente mejor tan pronto la simulación es interrumpida, los investigadores pueden gestionar para que alguien los guie a su hogar o a buscar atención medica si es necesario.

Los beneficios de participar en este estudio incluyen la adquisición de conocimiento sobre las condiciones del tráfico vehicular y el diseño de una carretera que inciden en la decisión de una persona para cruzar una carretera de manera segura, y también adquirir conocimiento sobre los factores humanos del comportamiento de los peatones.

7. ¿QUIÉN VERÁ LOS RESULTADOS Y/O MI DESEMPEÑO EN ESTE ESTUDIO?

Los resultados de esta investigación serán publicados en revistas de investigación científica y serán presentados en conferencias y simposios de entidades científicas profesionales. Los resultados podrían ser utilizados por los investigadores aprobados para propósitos internos. Ningún participante será identificable en los reportes o publicaciones ya que ni el nombre ni las iniciales de ningún participante serán utilizados. Para mantener confidencialidad de los archivos, los investigadores utilizarán códigos para identificar a cada sujeto, en vez de nombres, para toda la data colectada mediante cuestionarios y la data colectada durante su utilización del simulador. La data será asegurada en el Laboratorio de Ingeniería de Transportación de la Universidad de Puerto Rico en Mayagüez y solo será accesible por el investigador principal, y cualquier otro investigador aprobado para el estudio.

Es posible que su archivo de investigación, incluyendo información sensitiva y/o información de identificación, pueda ser inspeccionado y/o copiado por agencias federales o de gobierno estatal, en el curso del desempeño de sus funciones. Si su archivo es inspeccionado por alguna de estas agencias, su confidencialidad será mantenida en la medida permitida por la ley.

8. ¿RECIBIRÉ ALGUN TIPO DE COMPENSACION MONETARIA POR PARTICIPAR DE ESTE ESTUDIO?

No. Su participación en este estudio es completamente voluntaria.

9. ¿QUÉ PASA SI TENGO UNA PREGUNTA?

Si tiene alguna pregunta sobre el experimento o cualquier otro asunto relativo a su participación en este experimento, o si sufre de alguna lesión relacionada a la investigación como resultado del estudio, puede llamar al investigador, Natacha N. Cardona, al (787) 526- 3604 o vía correo electrónico a natacha.cardona@upr.edu, Alcibiades Bustillo, al (787) 451-4957 o vía correo electrónico a alcibiades.bustillo@upr.edu o el Dr. Alberto M. Figueroa, al (787) 832-4040 ext. 3465 o por correo electrónico a alberto.figueroa3@upr.edu. Si, durante el estudio o después de, usted desea discutir su participación o preocupaciones en cuanto al mismo con una persona que no participe directamente en la investigación puede comunicarse con el Comité para la Protección de los Seres Humanos en la Investigación del Recinto Universitario de Mayagüez al (787) 832-4040 ext. 6277 ó 6347 o cpshirum@uprm.edu. En caso de que el participante lo desee, una copia de este formulario de consentimiento informado será proveída para que la guarde en sus archivos.

10. ¿QUÉ PASA SI ME NIEGO A PROVEER MI CONSENTIMIENTO?

Su participación es voluntaria, por lo tanto, usted puede negarse a participar o puede retirar su consentimiento y dejar de participar en el estudio en cualquier momento y sin penalidad alguna.

11. ¿QUÉ PASA SI ME LESIONO?

Como usted es parte de la comunidad del Recinto Universitario de Mayagüez (ya sea empleado o estudiante) el seguro médico del Recinto le cubre en caso de tener algún riesgo o incomodidad.

12. DECLARACIÓN DE CONSENTIMIENTO VOLUNTARIO DEL SUJETO

Al firmar abajo, yo, el participante, confirmo que el investigador me ha explicado el propósito de la investigación, los procedimientos del estudio a los que voy a someterme y los beneficios, así como los posibles riesgos que puedo experimentar. También se han discutido alternativas a mi participación en el estudio. He leído y entiendo este formulario de consentimiento.

____________________________________ ____________
Nombre en letra de molde del participante Fecha

____
Firma del participante

13. DECLARACIÓN DEL EXPERIMENTADOR

Al firmar abajo, yo, el investigador, indico que el participante ha leído este Formulario de Consentimiento Informado y yo le he explicado a él/ella el propósito de la investigación, los procedimientos del estudio a los que él/ella va a someterse y los beneficios, así como los posibles riesgos que él/ ella puede experimentar en este estudio, y que él/ella ha firmado este formulario de consentimiento informado.

____ ____________
Firma de la persona que obtiene el consentimiento informado Fecha

Appendix C: Pre-Test Questionnaire

RECINTO UNIVERSITARIO DE MAYAGÜEZ
CAAM
UNIVERSIDAD DE PUERTO RICO

Fecha: ______________________

Número de participante: ________

LABORATORIO DE SIMULACIÓN DE CONDUCCION Y REALIDAD VIRTUAL CUESTIONARIO ANTES DEL ESTUDIO

El siguiente cuestionario es confidencial, la información que usted provea no será utilizada para conseguir su identidad. Usted será identificado con un número dado por el investigador, de esta manera se podrá validar la información obtenida durante la simulación. Tiene el derecho de no contestar cualquiera de las preguntas en este cuestionario.

SECCIÓN 1: DATOS DEMOGRÁFICOS

1. Indicar su edad: __________ años

2. Indicar su género:

☐ Masculino	☐ Femenino	☐ Prefiero no indicar

3. ¿Tiene usted alguna de las siguientes condiciones: diabetes, epilepsia, operación de la rodilla o tobillo o prótesis?

☐ Sí	☐ No

<u>Si su respuesta es SÍ en esta pregunta, favor de indicarlo de inmediato al investigador.</u>

4. ¿Experimenta síntomas de mareo al manejar o al ir de pasajero en un vehículo de motor?

☐ Sí	☐ No

<u>Si su respuesta es SÍ en esta pregunta, favor de indicarlo de inmediato al investigador.</u>

SECCIÓN 2: HISTORIAL DE EXPOSICIÓN DE RIESGOS COMO PEATÓN

1. Aproximadamente, ¿cuántos minutos al día camina usted por una carretera?

   ______ minutos

2. ¿Cuán confiado/a se siente usted de poder cruzar de manera segura una carretera de un carril en un lugar fuera de una intersección?

☐ Muy confiado	☐ Algo confiado	☐ Depende, Ni confiado Ni desconfiado	☐ Algo desconfiado	☐ Muy desconfiado

3. ¿Cuáles de los siguientes factores analiza usted para decidir cruzar una carretera fuera de una intersección? Marque con una X todas las que apliquen.

   _______ Velocidad del tráfico vehicular
   _______ Distancia disponible entre vehículos
   _______ Tiempo entre vehículos
   _______ Cantidad de vehículos
   _______ Ancho de la carretera
   _______ Otro: (Favor de indicar) ________________________________

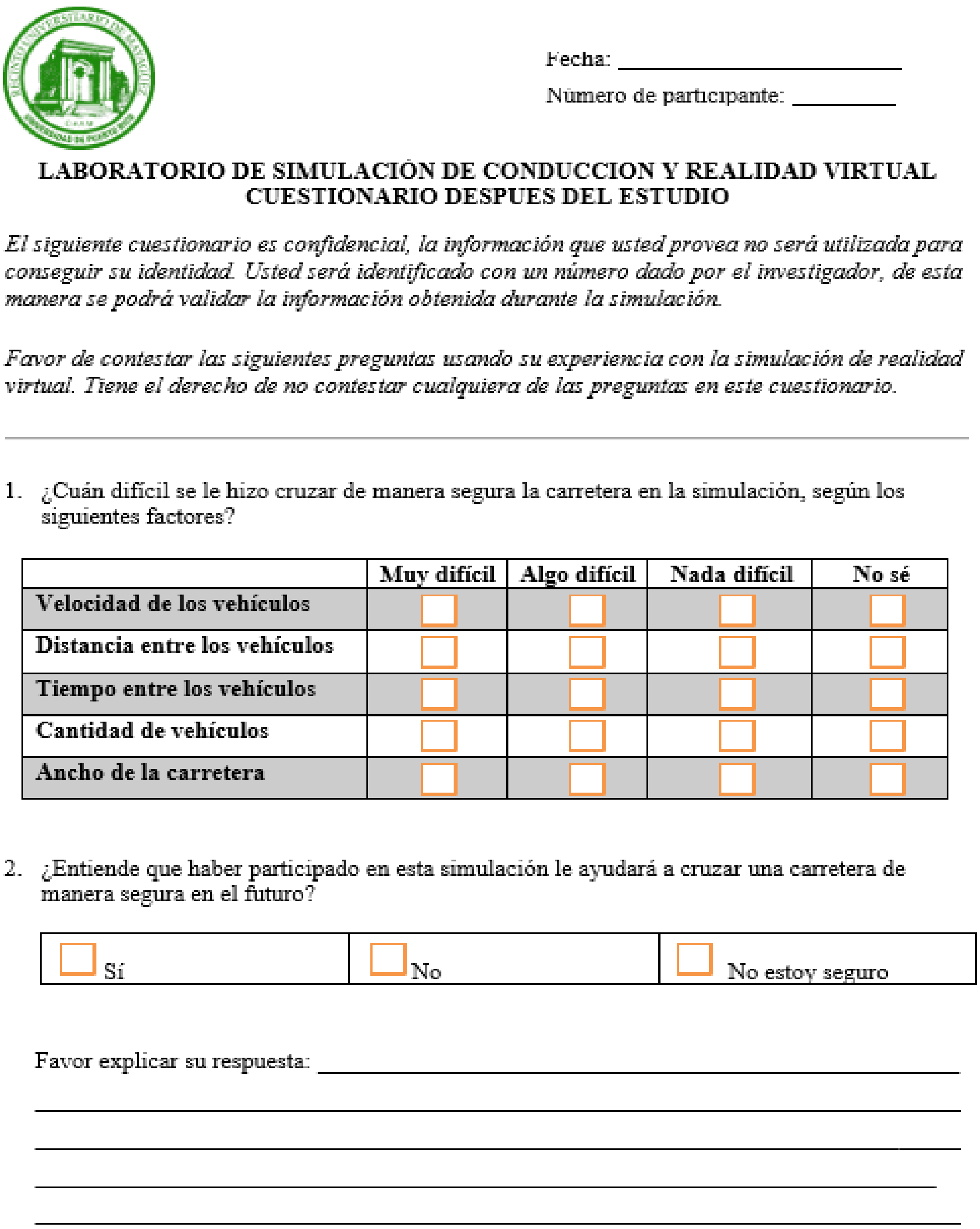
4. ¿Ha estado usted involucrado en algún accidente o choque de tránsito en los últimos 5 años?

☐ Sí	☐ No

Si respondió SI a la pregunta anterior, favor de indicar su relación con dichos eventos. Marque con una X todas las que apliquen.

   _______ Como conductor de un vehículo de motor
   _______ Como pasajero de un vehículo de motor
   _______ Como peatón
   _______ Como ciclista
   _______ Como usuario de e-scooter
   _______ Otro: (Favor de indicar) ________________________________

Appendix D: Post-Test Questionnaire



Fecha: ____________________________

Número de participante: __________

LABORATORIO DE SIMULACIÓN DE CONDUCCION Y REALIDAD VIRTUAL
CUESTIONARIO DESPUES DEL ESTUDIO

El siguiente cuestionario es confidencial, la información que usted provea no será utilizada para conseguir su identidad. Usted será identificado con un número dado por el investigador, de esta manera se podrá validar la información obtenida durante la simulación.

Favor de contestar las siguientes preguntas usando su experiencia con la simulación de realidad virtual. Tiene el derecho de no contestar cualquiera de las preguntas en este cuestionario.

---

1. ¿Cuán difícil se le hizo cruzar de manera segura la carretera en la simulación, según los siguientes factores?

	Muy difícil	**Algo difícil**	**Nada difícil**	**No sé**
Velocidad de los vehículos	☐	☐	☐	☐
Distancia entre los vehículos	☐	☐	☐	☐
Tiempo entre los vehículos	☐	☐	☐	☐
Cantidad de vehículos	☐	☐	☐	☐
Ancho de la carretera	☐	☐	☐	☐

2. ¿Entiende que haber participado en esta simulación le ayudará a cruzar una carretera de manera segura en el futuro?

☐ Sí	☐ No	☐ No estoy seguro

Favor explicar su respuesta: ____

____

____

____

____

3. ¿Cuán cómodo se sintió usted en la simulación de realidad virtual?

☐ Muy incómodo	☐ Algo incómodo	☐ Neutral	☐ Algo cómodo	☐ Muy cómodo

4. ¿Cuán seguro se sintió mientras utilizaba el equipo de realidad virtual?

☐ Muy inseguro	☐ Algo inseguro	☐ Neutral	☐ Algo seguro	☐ Muy seguro

5. ¿Cuán real usted percibió la simulación del ambiente virtual?

☐ Muy ficticia	☐ Algo ficticia	☐ Neutral	☐ Algo real	☐ Muy real

6. ¿Cómo cataloga usted la calidad de las siguientes características del ambiente virtual?

	Pobre	**Deficiente**	**Regular**	**Buena**	**Excelente**
Vehículos de motor	☐	☐	☐	☐	☐
Peatones	☐	☐	☐	☐	☐
Elementos físicos (árboles, edificios, etc.)	☐	☐	☐	☐	☐
Sonido	☐	☐	☐	☐	☐
Iluminación y sombras	☐	☐	☐	☐	☐

7. ¿Que mejoraría usted del escenario de realidad virtual?

____

____

____

____