Final Report

Implementing and Testing the Safety of Non-Motorized Road Users through Connected Everything and Traffic Signal Operations in Virtual Reality

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16. Abstract

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Abstract

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Introduction

Problem Statement

Despite their centrality in modern transportation planning, bicyclists and pedestrians still face significant safety risks in mixed traffic environments. In 2022, 7,522 pedestrians and 1,105 bicyclists were killed in traffic crashes in the United States (*1*, *2*). Compared to the year before, pedestrian fatalities saw a slight increase of 0.7% (*1*), while the number of bicyclists killed in traffic accidents saw a 13% increase (*3*). Most pedestrian (85%) and bicyclist (83%) deaths occurred in urban areas, where 23% of pedestrian and 34% of bicyclist deaths occurred at intersections (*4*, *5*).

Human factors are often implicated in bicyclists and pedestrian crashes. These can include limitations in perception, anticipation, and decision-making, which undermine mutual situational awareness between road users. Studies have shown that drivers tend to focus more on vehicles directly ahead and pay less attention to bicycles in their peripheral vision, increasing the risk of detection errors (*6*). Research has further shown that even when drivers visually fixate on a hazard, such as a pedestrian or a bicyclist, they may still fail to process or respond to it, so-called "look-but-not-see" errors (*7*). Bicyclists and pedestrians, in turn, face their own set of perceptual and cognitive challenges in navigating complex traffic environments. Urban arterials represent some of the most hazardous environments for pedestrians, accounting for a significant portion of traffic-related injuries and fatalities worldwide (*8*, *9*). Pedestrians often experience difficulties maintaining consistent attention at intersections, where such challenges are most common during crossing action due to distractions and environmental complexity (*10*). Conflicts frequently arise between pedestrians and turning vehicles, especially right-turning vehicles, leading to unsafe conditions (*11*, *12*). Bicyclists face challenges in allocating visual attention effectively at intersections, with varied crossing behaviors depending on intersection type, environmental conditions (*13*), route familiarity (*14*). The tendency to assume right-of-way often results in inadequate monitoring of approaching vehicles from critical directions (*14*). Conflicts with right-turning vehicles are particularly risky due to shared lane space and drivers' blind spots (*15*). Therefore, there is a pressing need for innovative strategies to improve the safety of bicyclists and pedestrians.

Originally developed for vehicle-centric applications, connectivity technologies are primarily designed to enhance safety and prevent collisions by providing drivers with critical information on the positions of other road users, weather conditions, nearby collisions, road conditions, and potentially hazardous activities (*16*). As these technologies have advanced, their scope has increasingly extended to bicyclists and pedestrians (*16–36*). In many cases, they are now not only able to share their information, but also receive from other road users or infrastructure. Connectivity encompasses a range of communication paradigms, including Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P), Vehicle-to-Bicyclist (V2B), and the broader Vehicle-to-Everything (V2X) technologies, all of which are increasingly tailored to address safety challenges. In parallel, a variety of safety applications, such as Forward Collision Warning (FCW), Blind Spot Warning (BSW), and VRU Collision Warning systems, have been developed (*37–39*).

Simulation environments, including driving, bicycling, and pedestrian simulators, offer a safe and controlled setting for the development and evaluation of connectivity technologies. By incorporating immersive Virtual Reality (VR) interfaces, these simulators are capable of preserving the perceptual realism and behavioral authenticity of real-world interactions while eliminating the physical real-world risks associated with complex traffic scenarios. Most existing studies have focused on the use of a single simulator with one human-controlled agent. However, Erdagi and Stevanovic (*40*) have developed and validated a novel Multimodal Virtual Reality Traffic Simulation (MVRTS) system that allows a driver, bicyclist, and pedestrian, each controlled by a human user, to interact in a unified simulation environment. Building upon this advancement, the present project leveraged the MVRTS system to test multiple connectivity strategies and safety applications for both drivers, bicyclists and pedestrians. In this framework, one group of experiments focused on pedestrian connectivity strategies, while another group examined bicycle–vehicle conflict scenarios under varying levels of connectivity.

To evaluate the system's performance under realistic traffic conditions, the project required a corridor with substantial multimodal demand. For this purpose, the system was developed and tested along Delaware Avenue, a roadway that runs through downtown Newark, Delaware, and traverses the core of the University of Delaware campus. This corridor is a two-lane, one-way eastbound roadway featuring a recently constructed separated bikeway equipped with dedicated bicycle signals (*41*). Despite these infrastructural improvements, several intersections along the corridor operate with permissive signal phases, and numerous unsignalized crossing points remain where vehicle trajectories intersect with those of bicyclists and pedestrians. These conditions underscore the ongoing need for strategies that mitigate conflict risks, particularly through connectivity-based solutions. Before such systems are implemented in the real world, their effectiveness and potential safety benefits should first be evaluated under controlled and safe simulation conditions. To this end, the present study leveraged digital twin technology to examine the impacts of connectivity applications on multimodal safety.

To replicate authentic multimodal traffic environments within simulation, we developed a high-fidelity digital twin of Delaware Avenue. The digital twin is supported by two tightly synchronized co-simulation platforms. CARLA (Car Learning to Act) (*42*), an open-source simulator platform, provides an immersive and realistic environment for human participants, while PTV Vissim 2025 (*43*) governs the surrounding background traffic dynamics. Within this integrated framework, we reconstructed controlled experimental scenarios to examine emerging applications such as V2P communications, collision warning systems (CWS) for bicycle–vehicle conflicts, and their consequent impacts.

Research Objectives

The goal of this project was to develop a multimodal traffic environment within a VR setup and evaluate various scenarios involving connectivity technologies for Bicyclists and pedestrians. To achieve this goal, we pursued the following two main objectives:

1. *Simulation and Experimental Development*: Develop a Digital Twin of a multimodal roadway network and integrate it into a human-in-the-loop simulation framework. Within this environment, design and implement a series of controlled experiments to test multiple connectivity technology scenarios and assess their potential impacts on Bicyclists and pedestrians.
2. *Impact Evaluation*: Using the established human-in-the-loop simulation, conduct experiments involving three types of roadway users—human-controlled drivers, bicyclists,

and pedestrians. These experiments aim to examine the influence of connectivity technology applications on participants' perception and anticipation of other road users, decision-making processes, perceived safety, stress responses, and stated preferences. Both subjective and objective data collection methods were employed, including participant surveys, trajectory data from simulation, and physiological measures.

Literature Review

The literature review encompasses several interrelated research domains. The first part focuses on state-of-the-art technologies related to digital twins, their conceptual foundations, functionality, and emerging applications within the transportation field. The second part reviews prior studies on vehicle-to-pedestrian communication systems, providing an overview of existing research that informed the design and analysis of the first group of experiments in this study. The third component presents a concise review of traffic conflict research, highlighting the methodological evolution from traditional real-world observations to microsimulation approaches and, more recently, to the use of driving simulators and VR technologies. The final section examines collision warning systems within bicycle–vehicle conflict scenarios.

Digital Twin Technology in the Transportation Domain

Digital twins (DTs) have emerged as a key enabling technology in realizing the vision of smart and connected infrastructure, characterized by seamless integration between the physical and cyber domains (*44*). Unlike conventional digital models, DTs maintain continuous two-way communication with their physical counterparts, enabling real-time synchronization, monitoring, and decision-making (*45*).

Within the transportation domain, DTs are increasingly recognized as foundational components of Intelligent Transportation Systems (ITS) (*46*). Several studies have reviewed how DTs extend the capabilities of ITS toward proactive, data-driven safety and mobility applications (*47–50*). Developing an accurate DT model in the transportation domain requires substantial data collection and advanced modeling techniques to capture the dynamic nature of traffic flow (*51*). In this context, a DT can be understood as a module that reproduces a detailed digital representation of the roadway, enabling realistic modeling and experimentation (*52*). Researchers have emphasized the importance of expanding simulation platforms such as SUMO (*46*, *53–55*), PTV Vissim (*56–58*), and CARLA (*46*, *59*, *60*), to serve as components of comprehensive DT frameworks for developing and testing emerging technologies and applications.

However, the DT concept in the transportation domain remains largely unstandardized, with diverse interpretations and philosophical approaches to cyber–physical integration. For instance, (*46*) developed a DT based on a real-world connected vehicle corridor, where the virtual model accurately replicated vehicle behavior, signal timings, communications, and traffic patterns within a simulated environment. Similarly, (*53*) applied SUMO simulation during system run-time, using actual traffic streams from motorway counters as live inputs to a synchronized DT. Expanding on this, (*54*) introduced a large-scale agent-based traffic microsimulation that fused empirical big data by integrating mobility information from cell phone records with conventional survey data. In (*55*), SUMO was coupled with OMNeT++ and Veins to virtualize V2X communications.

To create a dynamic DT for intersection monitoring and performance evaluation, (*56*) proposed a platform that integrated high-resolution LiDAR sensor data with PTV Vissim to enable continuous calibration of the microsimulation model. The same microscopic traffic simulation environment served as the DT engine in (*57*), supporting emulation and real-time traffic signal optimization through reinforcement learning, using both historical and real-time signal and volume data. Similarly, (*58*) adopted a DT approach to implement an Automated Traffic Signal Performance Measure (ATSPM) system within an in-the-loop simulation framework, coupling PTV Vissim with two full-scale ATSPM systems—the open-source platform and a big-data-enhanced module.

Beyond these traffic-control-oriented DTs, (*59*) leveraged the CARLA simulator to build a DT platform capable of providing real-time information about road objects such as vehicles and pedestrians, along with detailed roadway geometry. CARLA's open API architecture also facilitates integration with other simulation tools and real-world applications; for instance, (*60*) connected CARLA with Node-RED to develop and test a *Car-as-a-Service* (CaaS) system, demonstrating the potential of DT-based co-simulation for applied mobility services.

However, previous research has not clearly defined what a DT platform should represent in the context of human-in-the-loop simulations (HILS). For HILS applications, we propose that the development of a DT requires a high-fidelity platform that integrates a realistic three-dimensional replica of the study corridor and its surroundings with authentic traffic patterns and signal timings, providing human participants with an immersive and behaviorally accurate virtual experience. Such a framework aligns with the literature, suggesting that a DT should enable realistic modeling and experimentation (*52*). Accordingly, the *Methodology* section introduces a novel DT-based approach for HILS that functions as a physical–virtual replica of a real traffic network, supporting experiments under real-world operational conditions.

Vehicle-to-Pedestrian Communications

As cities transition toward integrating connectivity technologies within vehicles and infrastructure, understanding how pedestrians interact with these new technologies becomes increasingly critical (*61*). Traditional road users rely heavily on implicit cues such as eye contact and vehicle motion to infer driver intentions (*62*). However, these cues can be ambiguous, inconsistent, or easily overlooked, particularly when pedestrians are distracted by movement, mobile phone use, or other environmental factors. The risk is further exacerbated when pedestrians encounter aggressive or inattentive drivers who fail to yield or recognize pedestrian presence.

Vehicle-to-Pedestrian (V2P) communication presents a promising approach to enhancing pedestrian safety by enabling vehicles to explicitly share their intentions with nearby pedestrians (*63*). Numerous studies (*64–66*) have shown that V2P systems, such as auditory alerts, mobile notifications, or external human-machine interfaces (eHMIs), can improve pedestrian decision-making by providing timely and informative cues. For example, a range of experiments (*67–71*) have demonstrated that audio warnings and intention-sharing interfaces help pedestrians better anticipate vehicle behavior and decide when to cross safely. However, these studies primarily focus on idealized direct V2P communication, assuming widespread deployment of connected vehicles. In reality, the near-term deployment of V2P systems faces several critical limitations. Most notably, not all vehicles will be equipped with the necessary communication technologies, especially in the early stages of adoption, leading to inconsistent coverage and reliability. In such cases, connected infrastructure can serve a complementary role by using roadside sensors (e.g., LiDAR, radar, or cameras) to detect approaching unconnected vehicles and subsequently disseminate warnings to nearby pedestrians.

Among the many complex urban scenarios, intersections involving right-turning vehicles and crossing pedestrians represent one of the most frequent and hazardous conflict points in urban arterials (*12*). These scenarios often lead to safety-critical situations, as turning drivers must simultaneously monitor multiple streams of information, including oncoming traffic, traffic signals, and pedestrian crossings. While prior studies on vehicle–pedestrian interaction using VR have provided valuable insights, particularly in scenarios involving vehicle stops at stop signs or pedestrian crossings at unsignalized zebra crosswalks (*72*, *73*), there remains a significant research gap concerning right-turning vehicles at signalized intersections. Specifically, the role of signal timing, such as the duration of the pedestrian crossing time, and its influence on pedestrian crossing decisions in these conflict-rich scenarios has not been sufficiently explored. To address the limitation above, this study developed a VR platform to simulate intersection crossing scenarios involving right-turning vehicles with different levels of communication capability.

Evolution of Traffic Conflict Methodologies toward Virtual Simulation

A traffic conflict is generally defined as an observable event in which two or more road users approach each other in a manner that could potentially result in a collision (*74*). Such situations are often referred to as *near misses* or *critical incidents* that require evasive action to prevent an accident (*75*, *76*). In traffic safety research, the traffic conflict technique (TCT) has been widely used as an indirect method to identify conflicts and assess safety performance at urban intersections (*77*). When applying TCT to detect and classify severe conflicts, most studies rely on the trajectories of interacting agents, where the most common parameters in the literature are Time-to-Collision (TTC) (*78*) and post-encroachment time (PET) (*79*), both of which quantify the temporal proximity between two road users.

Early research on traffic conflicts was based on field observations of real-world interactions (*80*), but later evolved to incorporate traffic microsimulation models enhanced with the Surrogate Safety Assessment Model (SSAM) (*81*). Concerns remain regarding the capability of these models to accurately reproduce unsafe interactions and near-miss events among roadway users (*82*). More recent studies have employed driving and bicycling simulators to analyze conflict situations within virtual environments involving human participants (*83*) involving a human agent.

Nevertheless, research employing dual-simulator systems and DT technology, where two human agents coexist and interact dynamically within the same virtual environment, remains extremely limited. This raises a fundamental question: can a dual-simulator VR system realistically reproduce bicycle-vehicle conflict events as defined in traditional traffic conflict research (i.e., observable near misses involving evasive actions)? Moreover, given that both agents operate within a virtual environment, an additional question emerges, do participants actually perceive such interactions as conflict situations? To explore these questions, the present project designed an experimental setup that leads two human-controlled agents, a driver and a bicyclist, into potential conflict scenarios. The first objective was to determine whether such an experimental configuration could reproduce bicycle–vehicle interactions that meet conventional TTC and PET thresholds commonly associated with real-world severe traffic conflicts. The second objective was to examine whether participants within the VR environment *perceive* these interactions as genuine conflict situations. To this end, both physiological responses and self-reported measures were analyzed.

Collision Warning Systems for Bicycle – Vehicle Conflicts

Driver simulators have been widely used in evaluating collision warning systems. Bike-specific auditory cues improved hazard anticipation compared to horns (*84*), and visual warnings prompting driver actions were rated as most effective, especially in a two-stage format (*85*, *86*). Other studies found that advanced driver assistance and augmented reality warnings increased overtaking safety and driver clearance from cyclists (*87*, *88*).

The growing need to mitigate vehicle–cyclist conflicts has underscored the importance of integrating bicyclists into the same connected environment as motor vehicles. To support the development and testing of cyclist-focused collision warning systems, researchers have employed both field trials and controlled laboratory experiments, increasingly leveraging bicycle simulators to better understand cyclist behavior, preferences, and reactions in connected environments. Several promising prototypes of cyclist safety applications have emerged from this line of research.

In (*22*), a cyclist warning system was developed using GPS-based detection of danger zones, issuing auditory or tactile alerts for real-time hazard notification. Similarly, in (*23*), a multi-sensor forward collision warning system was created that accurately detected vehicles and supported collision avoidance. Complementing these technological developments, several studies have focused on how safety information should be conveyed to cyclists for maximum effectiveness and user acceptance. Studies show that cyclists prefer simple, clear safety alerts, with intuitive audio cues (headphones) favored over more intrusive smart-glass displays (*29*, *33*). As field trials cannot safely replicate high-risk conflicts, bicycle simulators provide a controlled yet realistic environment for studying cyclist behavior.

Several studies have leveraged simulators to evaluate cyclist-focused safety systems. For example, in (*36*), a Cooperative Adaptive Cruise Control system for cyclists was proposed, demonstrating safe spacing and reduced congestion risks. Similarly, a Virtual Cycling Environment with V2X communication and haptic alerts improved cyclist reaction times and reduced collisions (*31*). In (*34*), advanced driver assistance features were adapted for bicycles, in which Lane-Centric Assistance maintained lane position while reducing speed, cognitive workload, and effort. In addition to system functionality, simulator studies have also examined the effectiveness of different warning modalities in influencing cyclist behavior. A Collision Warning System improved situational awareness, leading to earlier braking and quicker visual fixations (*24*). In addition, auditory warnings produced the fastest reactions, outperforming visual and combined audio-visual alerts (*35*).

Prior research has advanced the understanding of how connectivity technologies affect vehicle–bicyclist conflict scenarios. However, most studies have relied on single-agent simulations, limiting insights into real-time interactions between human drivers and bicyclists. To address this gap, the present study introduces a novel framework that integrates two human agents within a shared, connected simulation environment.

Methodology

Digital Twin Development

The development of the DT used in this study involved multiple technical processes. An overview of the workflow is illustrated in **Figure 1**. These can be divided into two main components: (i) establishing the traffic microsimulation model, and (ii) creating the CARLA-based virtual environment.

Traffic Microsimulation Model: The base traffic microsimulation model, including traffic counts and signal timing plans, was provided by the Delaware Department of Transportation. This model served as the foundation for further development in PTV Vissim. The network geometry and control logic were exported into the OpenDRIVE format to provide a consistent digital representation of the Delaware Avenue corridor. This standardized file defined the roadway layout, traffic control elements, and operational rules that all virtual controlled agents (i.e., simulation-based vehicles) followed during the experiments. In PTV Vissim, traffic controllers at each intersection were connected to external Siemens SEPAC controllers via NTCIP communication protocols, enabling a software-in-the-loop simulation. This integration expanded the DT framework by incorporating real-world traffic controller logic and field-verified signal timings. However, for HILS experiments, external controllers were replaced with Ring-Barrier Controllers due to their greater flexibility and compatibility within the Vissim COM interface. In addition, a custom signal control algorithm was developed in Vissim to dynamically modify signal states based on the positions of human-controlled agents, thereby facilitating the creation of controlled conflict scenarios. (A detailed description of the algorithms is provided in the following section.)

CARLA Environment Development: The CARLA environment was designed to replicate the physical surroundings of Delaware Avenue while ensuring strict compliance with the standardized OpenDRIVE network. Development of this environment required the following steps:

1. **Rendering 3D Environment**: High-resolution 3D captures of the study area were obtained from Google Maps and processed using *RenderDoc* (version 1.2).
2. **3D Modeling**: The captured data were refined and merged in *Blender* (version 4.1) to construct detailed urban blocks. The outputs were exported as *.fbx* files representing the surrounding corridor environment.
3. **Integration of 3D Components:** Using *RoadRunner* (MathWorks), the OpenDRIVE network exported from Vissim was combined with the rendered 3D urban blocks. In this stage, OpenDRIVE served as the authoritative roadway skeleton, ensuring accurate lane-level geometry and coordinate system alignment. Static elements such as pavement markings, crosswalks, and road signs were then embedded into the network, creating a spatially consistent digital environment.
4. **Building the CARLA map:** The combined 3D environment (*.fbx*) and the OpenDRIVE file were subsequently imported into *Unreal Engine 4.26*. Unlike the previous step, here the role of OpenDRIVE was to provide runtime semantics: CARLA uses the OpenDRIVE specification to generate navigation waypoints, enforce lane-level rules, and synchronize traffic signal logic. Meanwhile, the *.fbx* models contributed the high-fidelity visuals. Additional dynamic objects, including traffic signal objects and VR-capable bicyclist and pedestrian agents, were then introduced. The output was a CARLA (version 0.9.15) package of the Delaware Avenue corridor.

5. **CARLA – PTV Vissim Synchronization:** To achieve real-time co-simulation, a Python-based synchronization module was developed. This module retrieves live signal phase data from Vissim and transmits corresponding updates to CARLA traffic signals. Conversely, it communicates the positions of human-controlled agents to Vissim, ensuring that background traffic responds to them as legitimate participants in the microsimulation. The synchronization is coordinated across three core scripts: *vissim_simulation.py* (managing Vissim operations), *carla_simulation.py* (controlling the CARLA environment), and *run_synchronization.py* (ensuring consistent two-way communication).

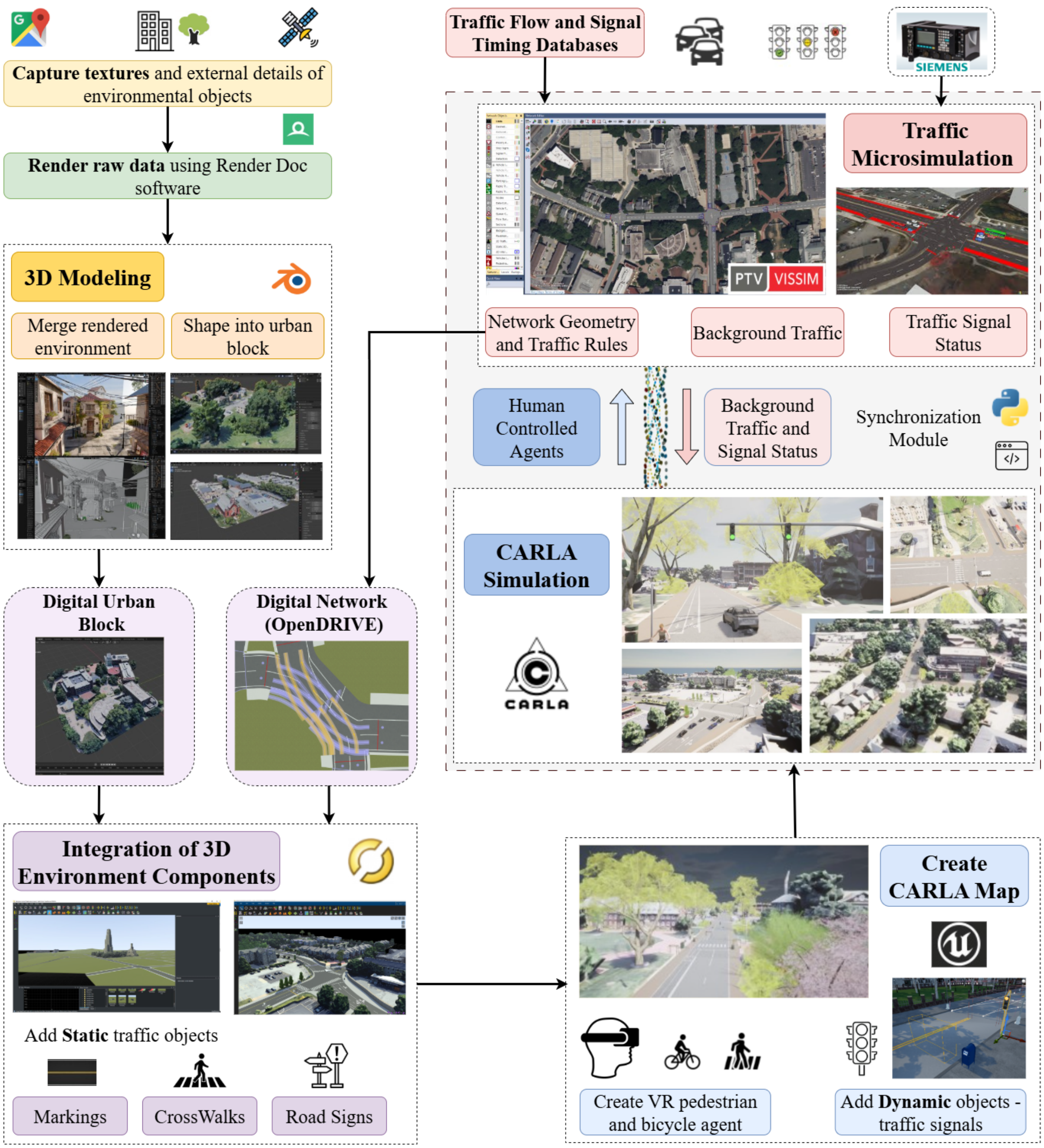


Figure 1: Digital Twin Development – Workflow

The final output of the DT, a comparison between Google Maps, the satellite view of the Delaware Avenue corridor, and the corresponding CARLA environment, is presented in **Figure 2**.

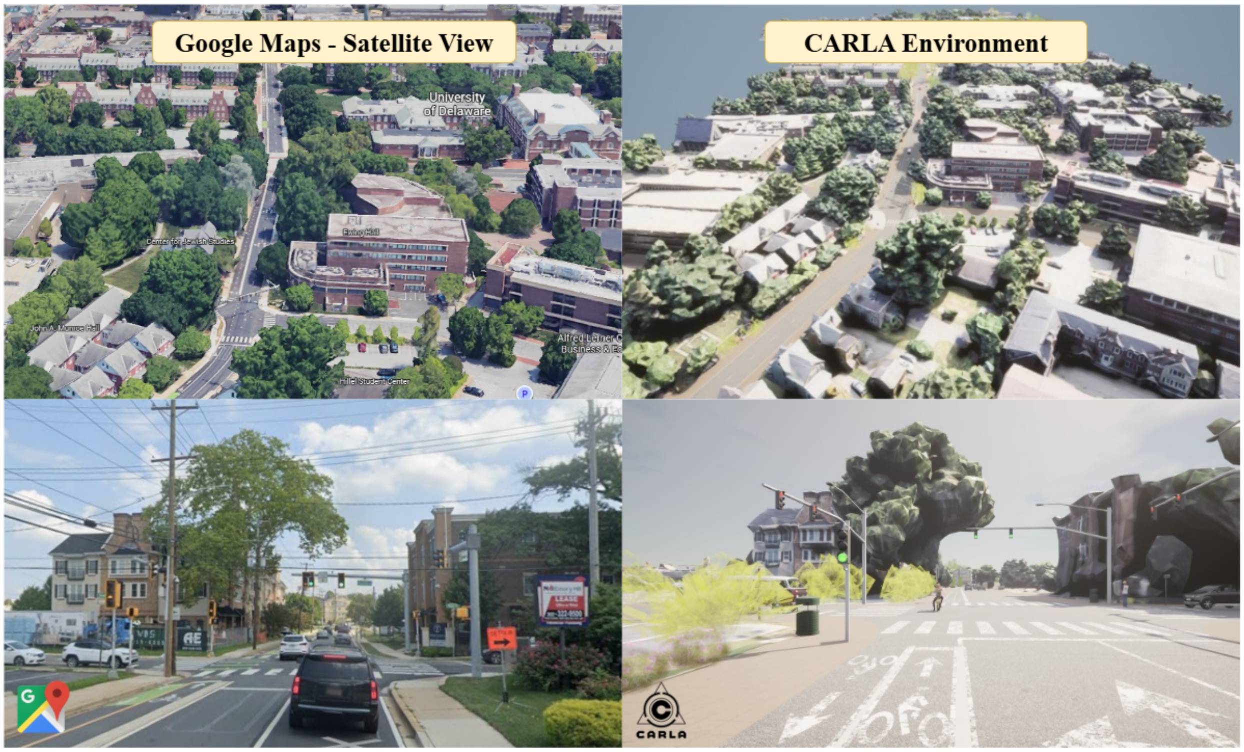


Figure 2: Comparison of the Digital Twin Environment and Google Maps Satellite View of the Delaware Avenue Corridor

Setup of Human-in-the-loop Simulation

Experiments are conducted in two physically distinct laboratories to demonstrate the distributed nature of the DT framework. The first set of experiments was carried out in the *Traffic Operations Laboratory* at the University of Virginia, focusing on the impacts of V2P communications and involving human-controlled pedestrian participants. The second set of experiments was conducted in the *Pittsburgh Intelligent Transportation Systems (PITTS) Laboratory* at the University of Pittsburgh, where the focus was on bicycle–vehicle conflicts under varying levels of connectivity, involving two human-controlled agents: a driver and a bicyclist.

Vehicle-to-Pedestrian Communication Experiments

The virtual environment mentioned above replicates a standard signalized intersection where a pedestrian crosswalk intersects with a right-turn vehicle lane. The simulation includes functional traffic signals with variable pedestrian crossing times and a predefined vehicle that approaches the crosswalk to execute a right turn at red, creating a potential conflict with the pedestrian's path, as shown in Figure 3. While participants experience the scenario from a first-person perspective, Figure 3 presents a third-person view of the experimental setup for reference.

(a) A participant wearing VR headset and holding the VR controller (b) First-person view of the participant at intersection in Carla environments

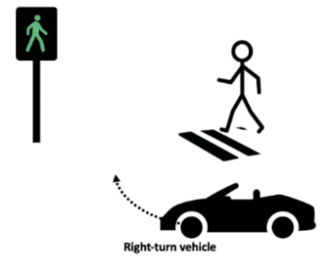
(c) Crossing pedestrian (d) Right-turning vehicle

Figure 3: A Participant with VR Devices in Simulated Environments with the Crossing Pedestrian, the Right-Turning Vehicle

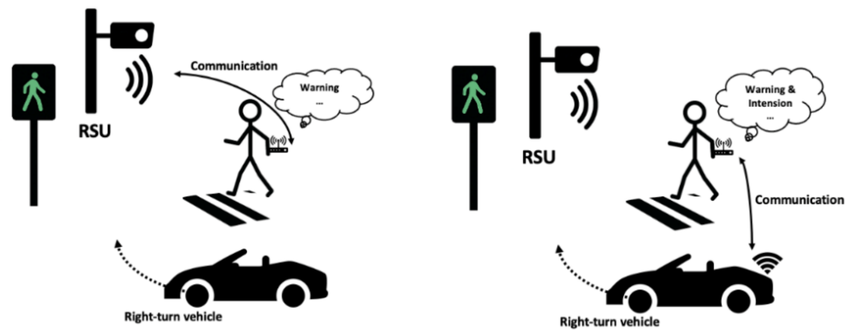
To enhance realism, additional background vehicles are programmed to circulate throughout the intersection; however, these vehicles do not interact with the participants and are included solely to simulate a natural traffic environment. The scenario design allows for controlled manipulation of three key experimental factors:

1. **Pedestrian crossing timing**: Two levels of pedestrian crossing timing are included, short and long pedestrian crossing times, each affecting the urgency and crossing decisions of the pedestrian.
2. **Communication condition**: The vehicle either remains silent, issues an auditory warning (partial communication), or provides both a warning and intention-sharing message (full communication) to pedestrians, as shown in Figure 4.
3. **Vehicle aggressiveness**: Aggressive driver behavior is considered in this study. The vehicle behaves aggressively and does not yield to pedestrians.

For the signal timing design, two scenarios were implemented: short and long pedestrian crossing times. In the short pedestrian crossing time condition, the short pedestrian crossing time is



(a) No communication



(b) Warning-based partial communication: a pedestrian with a connected device and the road side unit (RSU)

(c) Intent-sharing based full communication: pedestrians with connected devices and connected vehicles

Figure 4: Three Communication Scenarios in Experiments

designed to allow them to cross the intersection if they maintain their maximum walking speed. This means that if a pedestrian chooses to yield to an approaching vehicle, the remaining pedestrian crossing time may be insufficient to complete the crossing. This time constraint introduces pressure, potentially prompting pedestrians to rush or make more aggressive crossing decisions. Conversely, in the long pedestrian crossing time condition, pedestrians have enough time to cross the intersection, even after yielding to a vehicle. This setting reduces urgency and allows for more deliberate and cautious behavior. Prior to each trial, participants were informed about the characteristics of the upcoming signal timing to ensure they understood the constraints and could respond accordingly.

In scenarios involving V2P communication, auditory messages were delivered through the VR headset to simulate real-world communication channels. Under the partial communication condition, a general warning message, such as "*Warning: Watch for a right-turning vehicle.",* was provided. This form of communication represents an indirect interaction between pedestrians and traditional human-driven vehicles, where approaching vehicle information is detected by connected infrastructure and relayed to pedestrians via connected personal devices (e.g., smartphone apps, smartwatches).

In contrast, the full communication condition simulated direct communication between connected vehicles and pedestrians. Context-specific audio messages, such as "*Warning: A right-turning vehicle may not yield. Wait until safe.*", were used to convey the driver's intent. In this scenario, the driver of the connected vehicle had the option to actively indicate their intention to yield by pressing a designated button. If no input was received, the system inferred that the driver would not yield and communicated this information to the pedestrian accordingly. This setup allowed for a realistic evaluation of how varying levels of V2P communication, both indirect and direct, impact pedestrian decision-making and safety in conflict scenarios. These messages were designed to emulate realistic connected vehicle warnings and to assess their influence on pedestrian decision-making and perceived safety.

This study specifically focuses on scenarios involving aggressive vehicle behavior to better understand pedestrian responses under high-risk and conflict-prone conditions. Aggressive drivers, characterized by behaviors such as failing to yield, accelerating into turns, or exhibiting impatience, pose a disproportionately high threat to pedestrian safety at intersections. These situations often leave pedestrians with limited time and unclear cues for decision-making, increasing the likelihood of hesitation, unsafe crossings, or collisions. To capture authentic behavioral responses in these high-stakes scenarios, participants remained fully immersed throughout the experiment, completing all six scenarios sequentially without removing the headset. The simulation responded dynamically to their walking input and to the approaching vehicle's behavior, allowing for a responsive and context-aware environment that closely mirrored real-world pedestrian-vehicle interactions.

A total of 19 individuals participated in the experiment, comprising 11 males (58%) and 8 females (42%), with ages ranging from 18 to 40 years. Of these, 68% were undergraduate students and 32% were graduate students. The advertisement specified that the study would take approximately 30 minutes and involve evaluating pedestrian crossing behavior in a VR environment. Prior to the experiment, all participants were briefed on the study procedures and completed a brief training session to become familiar with the VR headset, handheld controller, and the interaction mechanism used to simulate walking and crossing.

Driver–Bicyclist Connectivity Experiments

The software framework supporting the experiments was described in the Digital Twin Development section of the methodology, where the CARLA–Vissim co-simulation platform served as the computational backbone of the process. To incorporate human participants into the VR environment, we employed an in-house simulation platform that enables multiple human agents to coexist and interact within the same virtual space (*40*), in this case, a driver and a bicyclist. The hardware infrastructure of the MVRTS system consisted of a high-fidelity driving simulator and a bicycle simulator, both integrated with the software platform to provide immersive and interactive experimental conditions.

Figure 5, left, illustrates the driving simulator, which provides an immersive virtual reality experience through a multi-screen setup. The driver operates the simulator using three 55-inch TV displays, offering a wide field of view and delivering a realistic yet conventional driving environment. The simulator chassis is outfitted with high-fidelity components, including a Sparco Chrono Road racing seat, a Cube Controls GT Pro Momo steering wheel, and Fanatec Clubsport V3 pedals, collectively enabling a highly realistic driving interface. The entire chassis is mounted on a D-BOX motion platform equipped with four 1.5-inch actuators, supporting three degrees of freedom (roll, yaw, and heave) to simulate vehicle movement dynamically. The simulation in action from the driver's perspective is shown in **Figure 6.**

The bicycle simulator features a standard road bicycle mounted on a Tacx Neo 2T smart trainer, which transmits speed and acceleration data to the simulation environment via Bluetooth. Steering input is captured using an Elite Sterzo Smart steering block, also connected wirelessly, enabling natural and responsive interactions with the virtual environment. This configuration allows bicyclists to make real-time adjustments in steering and pedaling in response to dynamic traffic conditions. A VIVE Pro VR headset provides the bicyclist with a fully immersive visual experience of the simulated environment. **Figure 5, right,** shows the VR bicycle simulator setup along with the bicyclist's perspective during the passing scenario. The VR experience of the bicyclist agent, including the corresponding field of view, is presented in **Figure 7**.

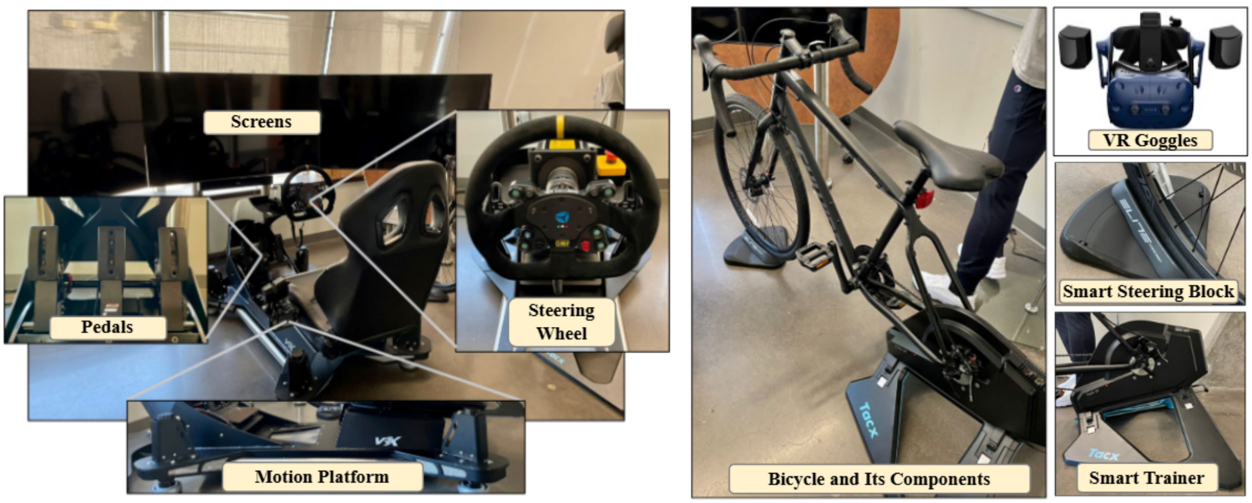


Figure 5: Multimodal Virtual Reality Traffic Simulation – Hardware Component: The Driving Simulator (left) and Bicycle Simulator (right)

Figure 6: The simulation in action from the driver's perspective

Figure 7: The VR experience of the bicyclist agent, and corresponding field of view

Experimental scenarios: Human drivers and bicyclists were guided through four scenarios based on their connectivity status. We selected three predetermined locations along the corridor where human agents could encounter one another. During the experiments, we collected trajectory data, physiological responses, and questionnaire responses, administered before the experiment, after each scenario, and upon completion of the entire session.

A mixed connectivity environment denotes traffic scenarios in which various agents, such as vehicles and bicyclists, possess different levels of connectivity. These scenarios include cases where: 1) neither agent is connected, 2) only one agent is connected (e.g., to smart infrastructure), or 3) both agents are connected. When referring to connectivity, experiments primarily focused on CWS, where smart infrastructure both detects relevant events and provides relevant information to the participants once both agents enter a designated conflict zone. Thus, four experimental scenarios were examined:

1. **Baseline Visual Awareness (No connectivity):** Agents rely solely on direct visual perception and existing traffic control.
2. **Partial Connectivity for the Bicyclist:** Connectivity is limited to the bicyclist through Bicycle-to-Infrastructure communication, allowing the bicyclist to receive Collision Warning Information (CWI).
3. **Partial Connectivity with the Driver**: Connectivity is limited to the driver of the vehicle through Vehicle-to-Infrastructure communication, allowing the driver to receive CWI.
4. **Full Connectivity:** Both the driver and the bicyclist are connected through Vehicle/Bicyclist-to-Everything communication, receiving real-time CWI.

Building on earlier findings (*29*, *33*, *35*, *85*), this project employed a communication framework in which connected bicyclists receive auditory warnings, while connected drivers are provided with visual alerts via a Head-Up Display. Alerts are implemented as context-specific, attention-directing cues tailored to intersection conflict conditions.

Design of Conflict Situations and Agent Route Configuration: Human agents exhibit unpredictable driving and cycling behavior in terms of speed selection, route choice, perceptual awareness, reaction to the surrounding environment, and overall capabilities. Taking these factors into account, this study predefined specific locations within the simulation where the ego driver and ego bicyclist could potentially encounter one another. This approach allowed for a balance between naturalistic behavior, which granted participants partial freedom in their driving or cycling, and controlled conditions, such as designated routes, recommended behavior patterns, and traffic signal manipulation to enhance the likelihood of conflicting situations.

Analyzing the current traffic regime of the corridor and estimating the traffic behavior of human agents, three key locations are identified along Delaware Avenue where potential conflict interactions could happen between the ego driver and the ego bicyclist. The agents' route remains consistent across all tested scenarios. The bicyclist departs from the Delaware campus and proceeds straight through each intersection using a dedicated bike lane. Meanwhile, the driver exits a parking lot adjacent to the corridor and performs a left-turn maneuver at each intersection, as shown in **Figure 8**. To ensure the driver re-enters Delaware Avenue after Intersection 2 (Academy Street), an additional network link (non-existent in the real world) was created at the northbound exit. The designed route includes four intersections: three where bicycle–vehicle interactions are expected, and an additional connecting intersection between the second and third to maintain route continuity and ensure the agents meet again at Intersection 3. The intersections are defined as follows:

- **Intersection 1:** An unsignalized intersection, exit from a parking lot, representing the first potential location for a conflicting situation.
- **Intersection 2:** A signalized intersection where the second conflict is designed to occur.
- **Intersection 3:** A signalized intersection designated as the third and final potential conflict location.

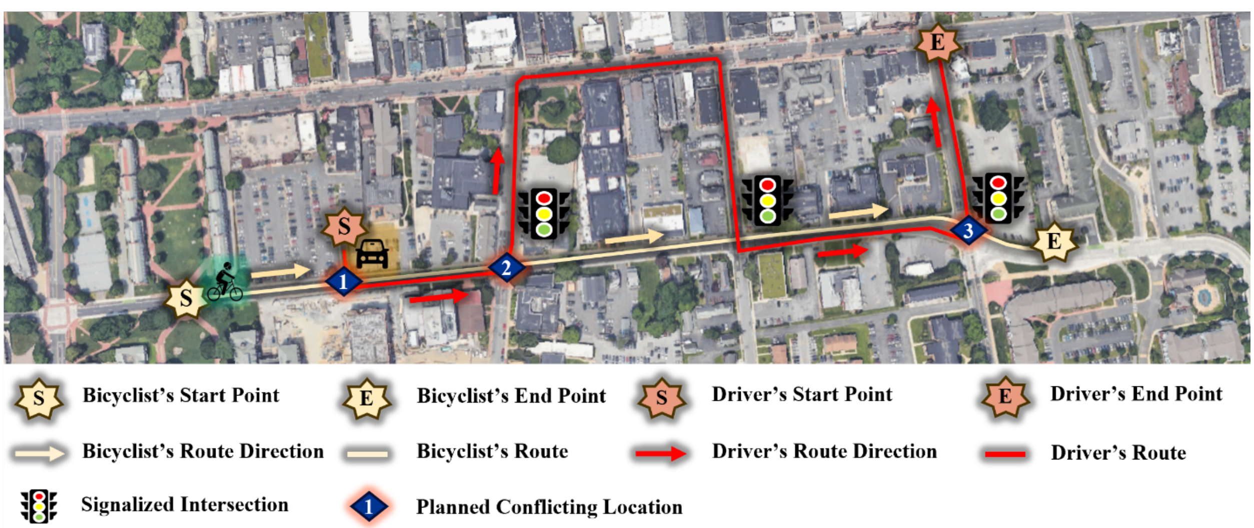


Figure 8: Experimental routes of driver and bicyclist

To execute these conflict scenarios at Intersections 2 (Delaware Ave – Academy St) and Intersection 3 (Delaware Ave – Chapel St), relevant traffic signal phases/heads were directly programed via PTV Vissim's COM interface. The signal control logic was designed to orchestrate a staged conflict sequence. Considering participants' freedom in speed choice and the natural speed differences between drivers and bicyclists, a tailored control strategy was required to ensure that both agents arrived at the intersection simultaneously, thereby creating the intended interaction.

Figure 9 illustrates the complete logic developed in the PTV Vissim COM interface. The signal control algorithm dynamically adjusts signal phases based on the positions of a human-controlled vehicle and a bicyclist approaching the same intersection. Each agent is assigned a unique identifier and tracked through its current approach link. The system first verifies whether both agents are located on valid approach links leading to the intersection. If this condition is met, the bicycle's distance to the stop line is calculated and used to determine signal control logic. When the bicycle is farther than a specific distance threshold 1 (DT1), both signals are set to red. When the bicycle is between two set thresholds, DT1 and DT2, the bicycle signal is set to green while the vehicle signal remains red, activating the existing bike-exclusive signal phase. When the bicycle is within pass DT2, both signals are set to green, creating a permissive phase. If either agent is not on a valid approach link, the special control logic is disabled and the intersection reverts to default signal operation.

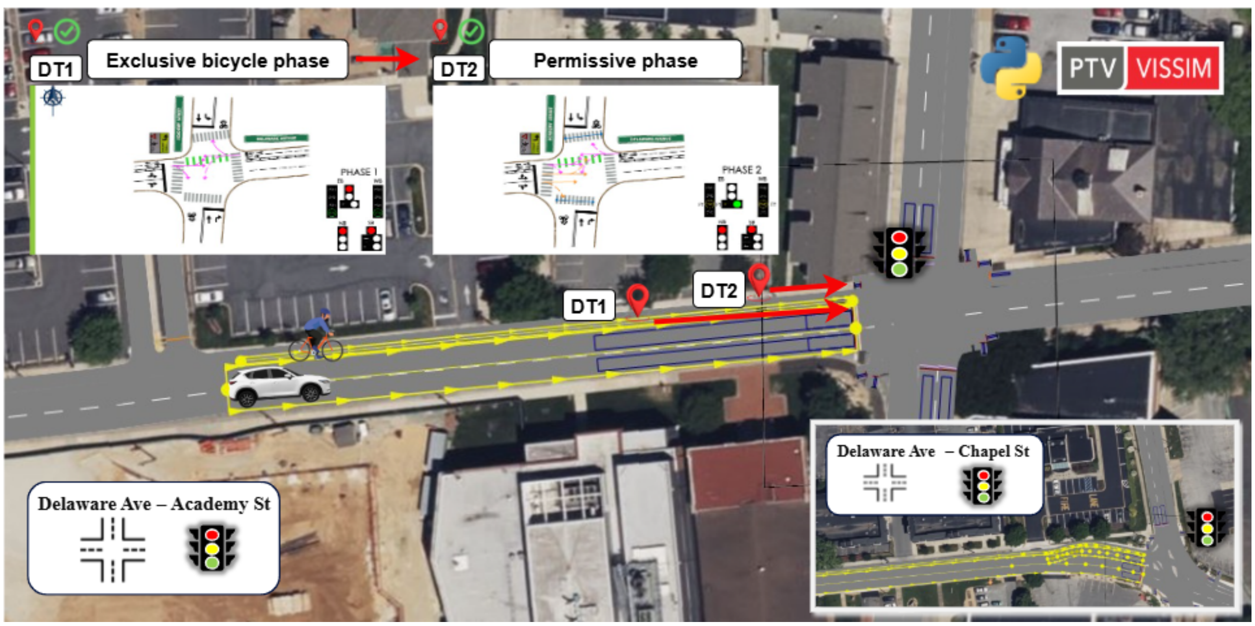


Figure 9: Signal Control Logic – Conflict Construction

Participants: In this project, a total of 17 participants were recruited to take part in experiments involving both driver and bicyclist roles. Among the bicyclist participants, 76% were male and 24% were female. For the driving role, 71% of the participants were male and 29% were female. The majority of participants (93% of bicyclists and 100% of drivers) were between the ages of 18 and 34, with most being undergraduate or graduate students at the University of Pittsburgh. Most participants were recruited to perform only one of the two roles, either as a driver or a bicyclist. In a few cases, when the same individual participated in both roles, a one-week interval was scheduled between sessions to reduce the likelihood of them memorizing specific details of the simulation environment and scenarios.

Drivers were required to hold a valid driver's license, while participants assigned to the bicyclist role had either regular or occasional cycling experience. All participants volunteered to take part in the study and were informed of their right to withdraw at any time, particularly due to the possibility of simulator-induced motion sickness in the virtual reality environment. Given that 47% of drivers and 57% of bicyclists reported limited prior experience with driving and bicycling simulators, respectively, all participants were given sufficient time before the experiments to become familiar with the simulator system and the DT of the study corridor.

Data Collection and Performance Matrix: To assess participants' sociodemographic profiles, driving and cycling characteristics, and experience, a pre-driving/cycling questionnaire was administered prior to the experiment. In addition, post-experiment surveys were used to measure participants' self-reported perceptions of conflict situations (ability to observe the other user) and anticipation (ability to predict a potential collision) on 5-point Likert scales.

To analyze participants' movement throughout the corridor and to calculate safety-related outcomes, trajectory data were continuously recorded during the experiment using CARLA's Python API. This enabled precise tracking of user behavior across all simulation scenarios.

For physiological data during the simulation, HR was recorded for both users using the Polar H10 chest strap. Skin Conductance (SC) data were collected from the bicyclist to gain deeper insights into their physiological arousal and emotional response. SC data were obtained using the BITalino EDA sensor, while Open Signals software was employed for signal acquisition and logging.

To synchronize simulation-derived data with physiological responses, the Lab Streaming Layer (LSL) framework was employed (*89*), enabling the seamless integration of multimodal datasets into a unified, time-synchronized format. Sensor and trajectory data were captured and managed using Lab Recorder, an LSL-compatible recording tool, which facilitated the alignment of simulation events with corresponding physiological signals for subsequent analysis.

Hazardous bicycle-vehicle interactions within the simulation were identified leveraging the Surrogate Safety Assessment Model (SSAM) (*81*), which analyzed trajectory data obtained from the CARLA simulation environment in order to compute TTC and PET. The computational methodology for both TTC and PET is illustrated in **Figure 10**.

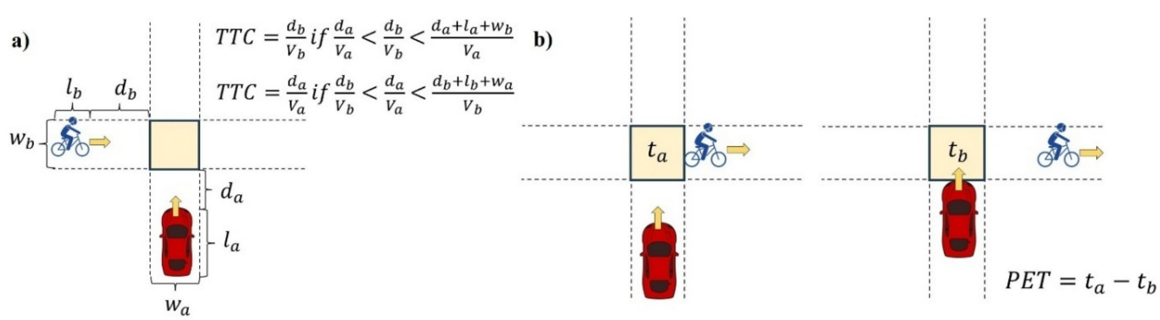


Figure 10: Surrogate Safety Assessment Model: a) TTC; b) PET

Results and Discussions

Impacts of Vehicle-to-Pedestrian Communication

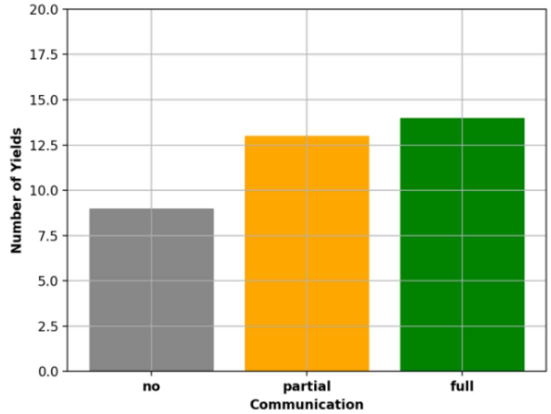
Influence of Communication on Pedestrian Behavior: **Figures 11** and **12** collectively illustrate the significant impact of V2P communication on pedestrian behavior across both short and long pedestrian crossing times. In scenarios without communication, collisions occurred under short pedestrian crossing time (2 cases), while no collisions were observed in partial or full communication scenarios in either pedestrian crossing time condition. This clearly indicates that the presence of communication, whether in the form of a basic warning or full intent-sharing, can substantially enhance pedestrian safety by reducing conflict risk.

In terms of yielding behavior, communication consistently encouraged more cautious decision-making. Under short pedestrian crossing time, the number of pedestrians who yielded increased from 9 (no communication) to 13 (both partial and full communication). This shows that even under time pressure, participants responded to warnings and intent-sharing messages by deferring their crossing for safety. A similar pattern was observed under long pedestrian crossing time, where yielding behavior remained uniformly high (13 yields) across all communication types. This suggests that communication reinforces a conservative mindset, even when sufficient crossing time is available.

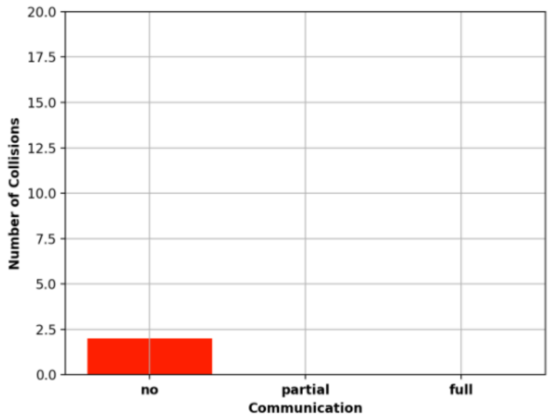
However, the increase in caution came with a trade-off in crossing efficiency, particularly under short pedestrian crossing times. As shown in **Figure 11**, the number of successful crossings dropped from 12 in the no-communication condition to 9 in both communication conditions, indicating that some participants opted to wait rather than risk crossing in conflict, even when it meant not completing the crossing in time. In contrast, under long pedestrian crossing time (Figure 12) the success rate remained optimal (18 in all cases), implying that communication had no adverse effect on crossing efficiency when time was not a limiting factor.

Effect of Pedestrian Crossing Duration: Pedestrian crossing time duration played a notable role in shaping pedestrian decision-making and yielding behavior across different communication scenarios. As illustrated in **Figures 11** and **12**, pedestrian crossing time duration significantly influenced pedestrian behavior, particularly in terms of yielding and crossing success. Under short pedestrian crossings, participants experienced greater time pressure, which led to more risk-taking behavior and a higher likelihood of conflict. This is evidenced by the occurrence of two collisions in the no-communication condition, while no collisions occurred under either partial or full communication. In contrast, no collisions were recorded under long pedestrian crossing time conditions across all types, suggesting that extended crossing time improves safety, even in the absence of vehicle warnings.

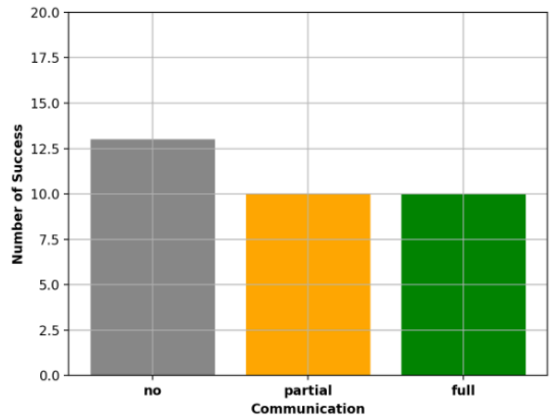
Yielding behavior also varied between the two pedestrian crossing time conditions. Under short pedestrian crossing time, the number of yields increased notably with the presence of communication, rising from 9 (no communication) to 13 and 13 (partial and full communication, respectively), indicating that pedestrians became more cautious when given auditory or intention-sharing information. Under long pedestrian crossing time, however, yielding was high across all communication types (13 yields in each case), suggesting that extended time alone encourages more conservative decision-making, regardless of communication.



(a) The number of yields

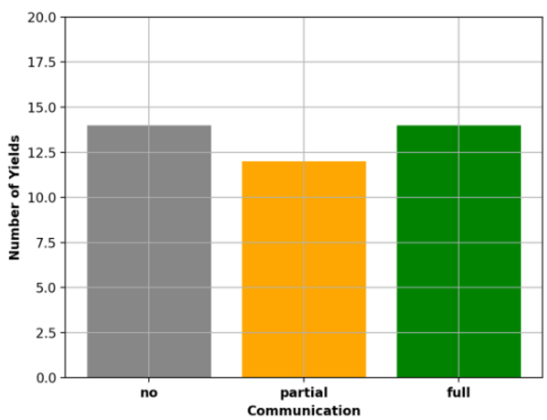


(b) The number of Collisions

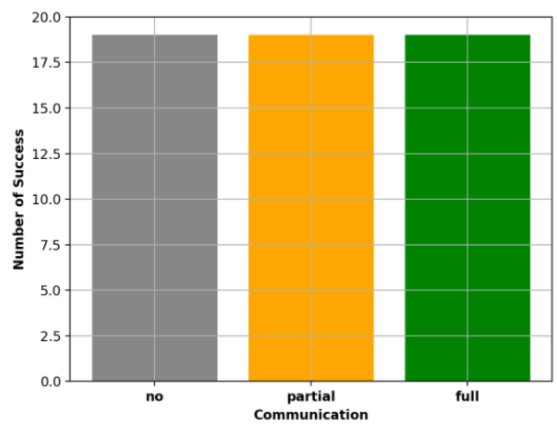


(c) The number of successful passes

Figure 11: Performance of crossing behaviors at the intersection with a short pedestrian crossing time



(a) The number of yields



(b) The number of successful passes

Figure 12: Performance of crossing behaviors at the intersection with a long pedestrian crossing time

Interestingly, crossing success rates show an opposite trend. Under short pedestrian crossing time, the success rate dropped in communication scenarios (from 12 in no communication to 9 in both partial and full communication), implying that increased yielding behavior in response to warnings caused pedestrians to delay crossing and miss the short pedestrian crossing time. In contrast, under long pedestrian crossing time, the number of successful crossings remained consistently high (18 across all communication types), demonstrating that when time pressure is removed, communication no longer compromises crossing completion.

These results highlight that communication plays a critical role in short pedestrian crossing time settings by enhancing safety, but may inadvertently reduce crossing efficiency due to increased caution. Conversely, long pedestrian crossing time durations support both safety and efficiency, even without communication, by allowing pedestrians sufficient time to evaluate and respond to approaching vehicles. This underscores the importance of considering pedestrian crossing time duration when designing V2P communication systems and pedestrian crossing time policies.

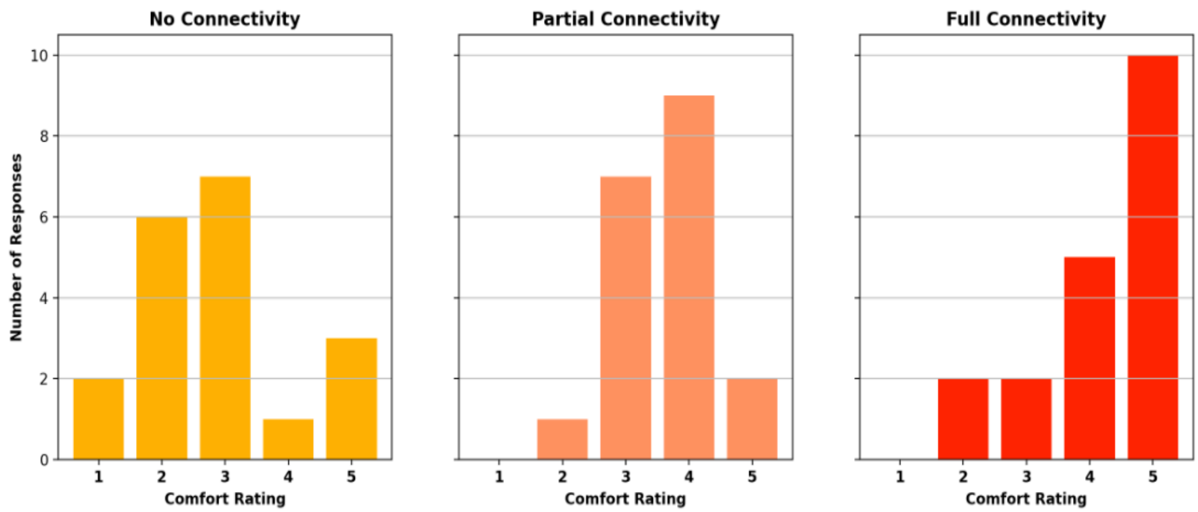


Figure 13: Comfort level reported by 19 participants after experiments

Participant Survey Insights: Participant comfort levels varied notably depending on the communication scenario, as illustrated in **Figure 13**. In the "no connectivity" condition, comfort ratings were generally low, with the majority of responses clustered around ratings of 2 and 3, and only 3 participants rating their experience as very comfortable (rating 5). This suggests that in the absence of vehicle communication, pedestrians experienced heightened uncertainty or perceived risk when making crossing decisions, likely due to the lack of feedback on vehicle behavior.

In contrast, partial connectivity, which included basic auditory or warning cues, produced a marked improvement in perceived comfort. Most responses shifted toward higher ratings, with 4 emerging as the most frequent score. This indicates that even minimal communication from vehicles can significantly enhance pedestrians' situational awareness and reduce perceived stress. The most substantial increase in comfort occurred under the full connectivity scenario, where vehicles not only warned but also shared their intentions explicitly. Here, rating 5 (very comfortable) received the highest number of responses, followed by rating 4, suggesting that comprehensive V2P communication promotes a strong sense of security and control among pedestrians. Importantly, no participant rated this scenario below a 2, highlighting the consistently positive perception of full connectivity. These findings demonstrate that increasing the level of vehicle communication directly correlates with improved pedestrian comfort, reinforcing the value of implementing advanced V2P communication systems to enhance user experience and encourage safer crossing behavior in complex intersection environments.

Bicycle-Vehicle Conflicts

The primary objective of this experiment was to generate bicyclist–vehicle interactions that escalate into conflict situations—specifically, to determine whether the experimental setup could reproduce interactions falling within TTC and PET thresholds commonly adopted in the literature. Furthermore, the study aimed to examine whether participants *perceive* these events as conflict situations by analyzing their self-reported assessments and physiological responses.

Conflict Identification: In the literature, the most adopted PET threshold for identifying severe conflicts is 1.5 sec (*90*, *91*). Initially, the same threshold was considered for the TTC indicator in general traffic conflict studies (*92*). However, research specifically examining bicycle–vehicle interactions has focused on a higher TTC threshold of 2 s (*86*, *93*). Accordingly, in this study, severe conflicts were identified from the designed bicycle–vehicle interactions using criteria of TTC < 2 s and PET < 1.5 s, across all three intersections and four connectivity scenarios. **Figure 14** illustrates the spatial layout of the three intersections, while **Figure 15** presents the number of events detected based on the TTC and PET criteria.

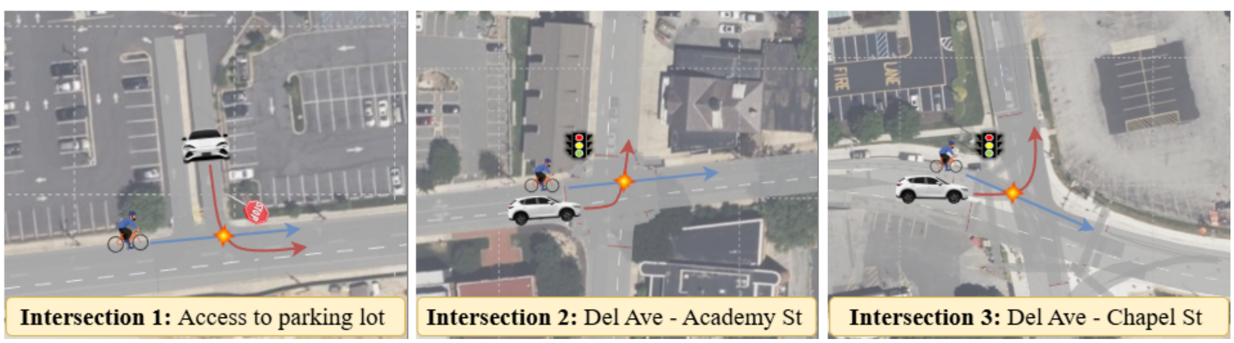


Figure 14: Layout of the Intersections Used for Bicycle-Vehicle Conflict Analysis

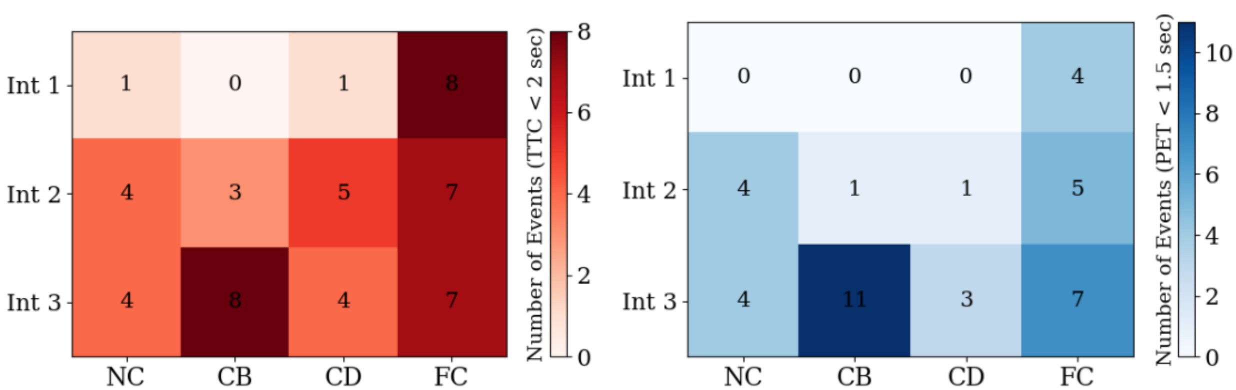


Figure 15: Number of Detected Events Based on TTC (left) and PET (right) Criteria Across Connectivity Scenarios

As shown in **Figure 15**, the experimental setup consistently generated bicyclist–vehicle interaction events with a TTC of less than 2 seconds and a PET of less than 1.5 seconds at all intersections. Each intersection recorded at least ten such events based on the TTC criteria, with Intersection 3 showing the highest frequency of interaction events. Intersection 2 also exhibited a relatively high number of TTC-<-2-sec events, likely because, unlike intersection 1, where the driver approaches the main corridor with the bicyclist typically in their frontal field of view, intersections 2 and 3 feature permissive left-turn phases where the bicyclist is often positioned in the driver's blind spot.

The fully connected (FC) environment produced the greatest number of TTC- and PET-based critical events at Intersections 1 and 2, whereas the scenario in which only the bicyclist was connected (CB) resulted in the highest number of events at Intersection 3. These findings suggest that both FC and CB scenarios generated greater number of TTC- and PET-based critical events compared to the no-connectivity environment (NC) and the environment where only the driver is connected (CD), that is, in literature presented as surrogate exposure (*94*). A higher number of encounters, that is, a shorter temporal proximity between the two road users, which, however, does not necessarily indicate higher levels of actual risk or unsafe conditions.

The subsequent analysis focused on different TTC events to examine whether participants *perceived* those events as conflicts based on their self-reported statements. For each intersection along their route, participants were asked whether they experienced an interaction with a turning vehicle/crossing bicycle that they would classify as a conflict. Furthermore, a cross-analysis was conducted by categorizing their responses according to three TTC groups: (1) TTC < 2 seconds, typically considered a severe conflict in the literature; (2) 2 seconds < TTC < 5 seconds, representing moderate interactions; and (3) TTC > 5 seconds, indicating non-critical situations. The distributions of responses for both the bicyclists and drivers are presented in **Figure 16**.

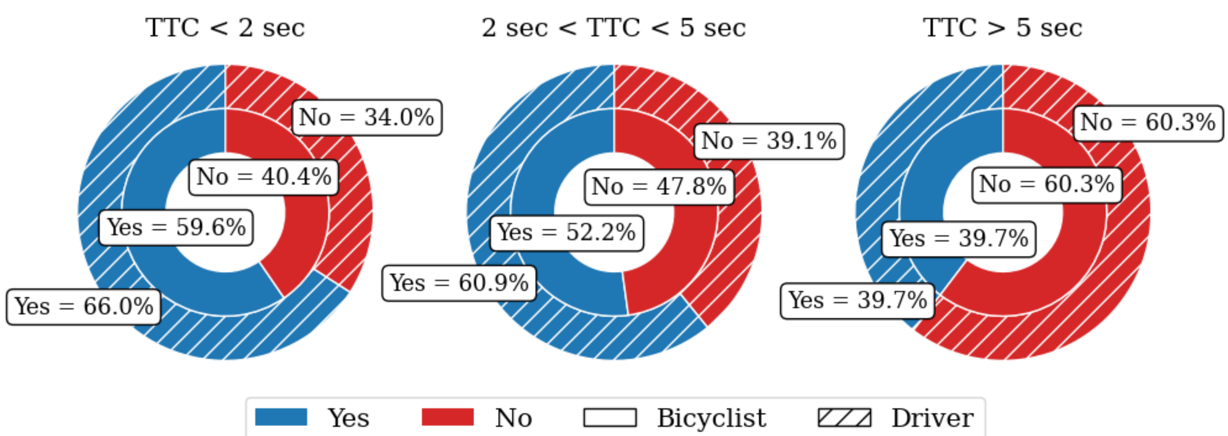


Figure 16: Participants' self-reported assessment of conflict with turning vehicles, categorized by Time-to-Collision (TTC) groups

From **Figure 16**, it can be observed that the majority of both bicyclists and drivers perceived TTC < 2 sec events as conflict situations. In this 'severe-conflict' category, 66% of drivers self-reported these events as conflicts, compared to 59.6% of bicyclists. Furthermore, a considerable proportion of participants also perceived TTC values between 2 and 5 sec as conflicts (although to a lesser extent), where 60.9% of drivers and 52.2% of bicyclists reported such interactions as conflicts. In contrast, for events with TTC > 5 sec, most participants did not perceive them as conflicts; in fact, 60.3% of both groups reported these events as *non-conflict* situations.

Overall, these findings suggest a clear inverse relationship between TTC magnitude and participants' perception of conflict: as the TTC increases, the likelihood of participants identifying an event as a conflict decreases. Additionally, across both the severe and moderate TTC ranges, drivers consistently reported a higher perception of conflict compared to bicyclists, indicating a possible difference in situational awareness or perceived risk between the two user groups.

Further analysis focused on TTC < 2 sec events to validate these occurrences as stressful conflict situations based on participants' physiological responses. Throughout the experiment, drivers' heart rates (HR) and bicyclists' HR and skin conductance (SC) were continuously recorded. To account for inter-individual variability, HR and SC data were standardized using Z-score normalization (*95*), where each participant's route-level mean was set to zero and deviations were expressed in standard deviation units. Positive Z-scores indicate HR or SC values above the individual mean, while negative values indicate below-mean responses. **Figure 17** shows average HR and SC Z-scores for TTC < 2 sec events, averaged over a 5 sec window before and after the interaction moment, defined as the time when the first agent entered the conflict point.

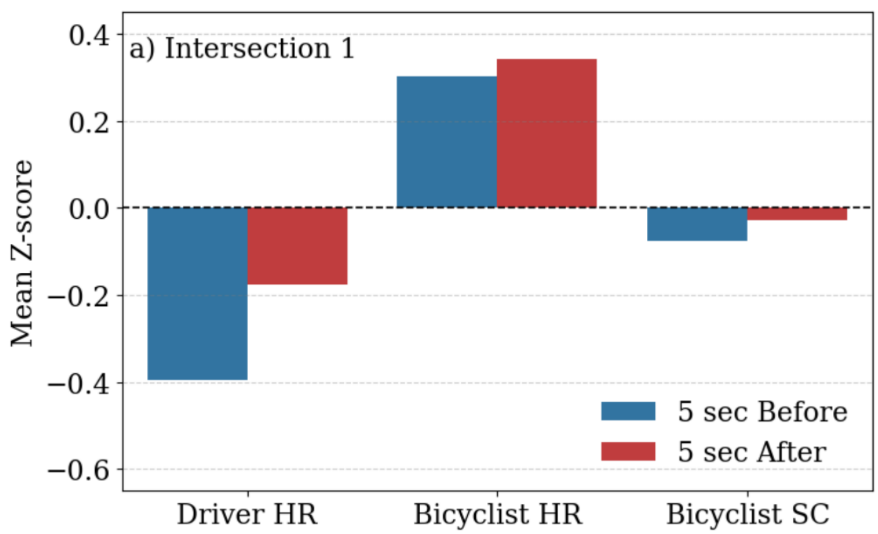


Figure 17: Drivers' and Bicyclists' Physiological Response (HR and SC Z-scores) at Intersection 1

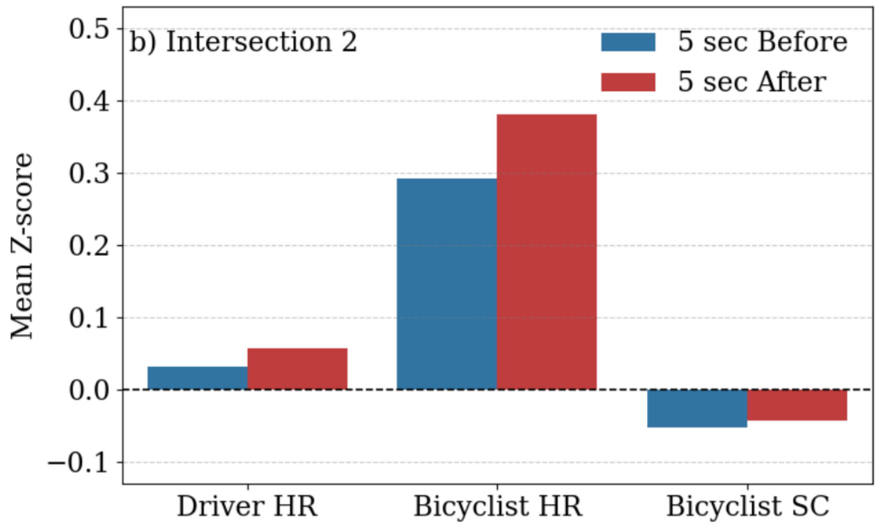


Figure 18: Drivers' and Bicyclists' Physiological Response (HR and SC Z-scores) at Intersection 2

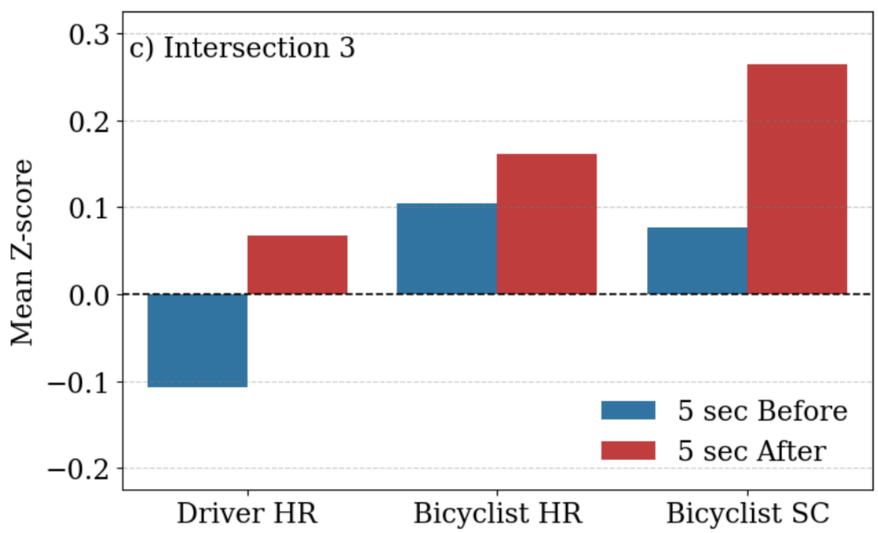


Figure 19: Drivers' and Bicyclists' Physiological Response (HR and SC Z-scores) at Intersection 3

As shown in **Figure 17**, both drivers and bicyclists exhibited higher average HR Z-scores within five seconds after the TTC < 2 sec event compared to five seconds before the event. A similar trend was observed in SC, where bicyclists showed elevated SC Z-scores following the interaction moment, indicating increased physiological arousal. These consistent patterns were observed across all three intersections. When the first agent entered the crossing point, it triggered a measurable physiological response, suggesting that participants experienced these events as stressful situations rather than neutral interactions. Considering that TTC < 2 sec events were perceived by participants as conflicts based on their self-reported statements and physiological responses indicating elevated stress, we can conclude that the designed interactions within the VR environment successfully reproduced realistic bicycle–vehicle conflict situations.

Perception and Anticipation: The next stage of the analysis examines the impacts of CWI on participants' perception of the other road users and their anticipation of potential conflicts with them. Both parameters were evaluated using survey responses collected after each experimental scenario. Perception was assessed through a question asking participants to rate their ability to detect the other party at the intersection in that specific scenario. Anticipation was assessed by asking whether they were able to anticipate that a potential conflict could occur based on the other user's movement. Accordingly, **Figure 18** compares drivers' and bicyclists' perception and anticipation scores across the four experimental scenarios.

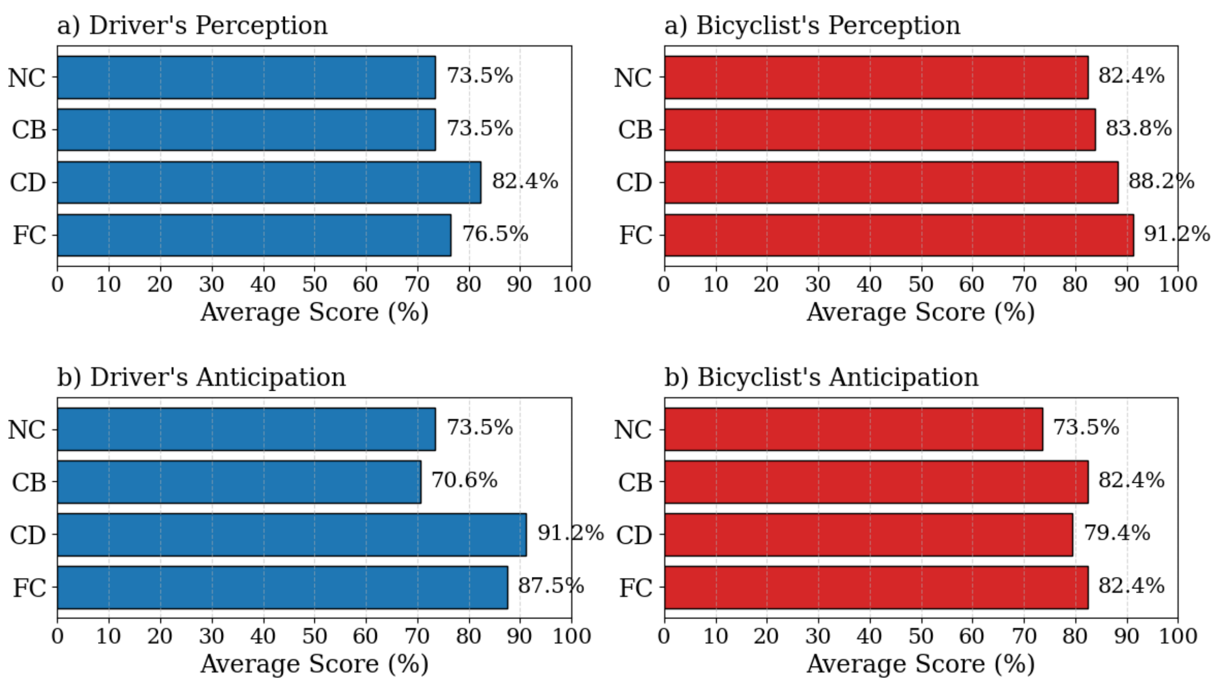


Figure 18: Drivers' and Bicyclists' Perception and Anticipation

Results in **Figure 18** show that drivers reported lower perception and anticipation abilities in scenarios where they didn't receive CWI (NC and CB) compared to scenarios where they as connected users (CD and FC) received information about bicyclists that were heading in their direction. These results are most likely a consequence of the blind-spot challenge inherent in left-hook conflicts. By contrast, the introduction of CWI to the drivers substantially improved their performance in both measures, with connected-driver scenarios yielding the strongest gains in both parameters.

For bicyclists, CWI (CB and FC) enhanced anticipation, enabling them to better predict conflicting situations based on the driver's movement. However, perception scores improved significantly only in the fully connected environment (FC), while the bicyclist-connected scenario (CB) did not outperform the unconnected condition (CD). These outcomes can be explained by the fact that anticipation improves directly through the provided CWI, whereas perception may also depend on behavioral changes from the other party, a point that is examined in the further analysis.

Decision-Making: This stage of the analysis focused on Intersections 2 and 3, where the same conflict type occurred, specifically, a left-turning vehicle crossing the bicyclist's path. Participants' decision-making was examined through their speed profiles, represented by average speed values. The analysis considered three phases of speed behavior: (1) the approach speed prior to receiving the CWI, (2) reaction-related speed adjustments within two seconds after receiving the CWI, and (3) post-reaction speed changes within three seconds following the reaction.

The further analysis examined behavioral adaptation across Intersections 2 and 3, evaluating whether participants reduced their approach speeds at Intersection 3 after experiencing a serious conflict at Intersection 2. **Figure 19** illustrates these patterns, showing approach, reaction, and post-reaction speed adjustments at Intersections 2 and 3.

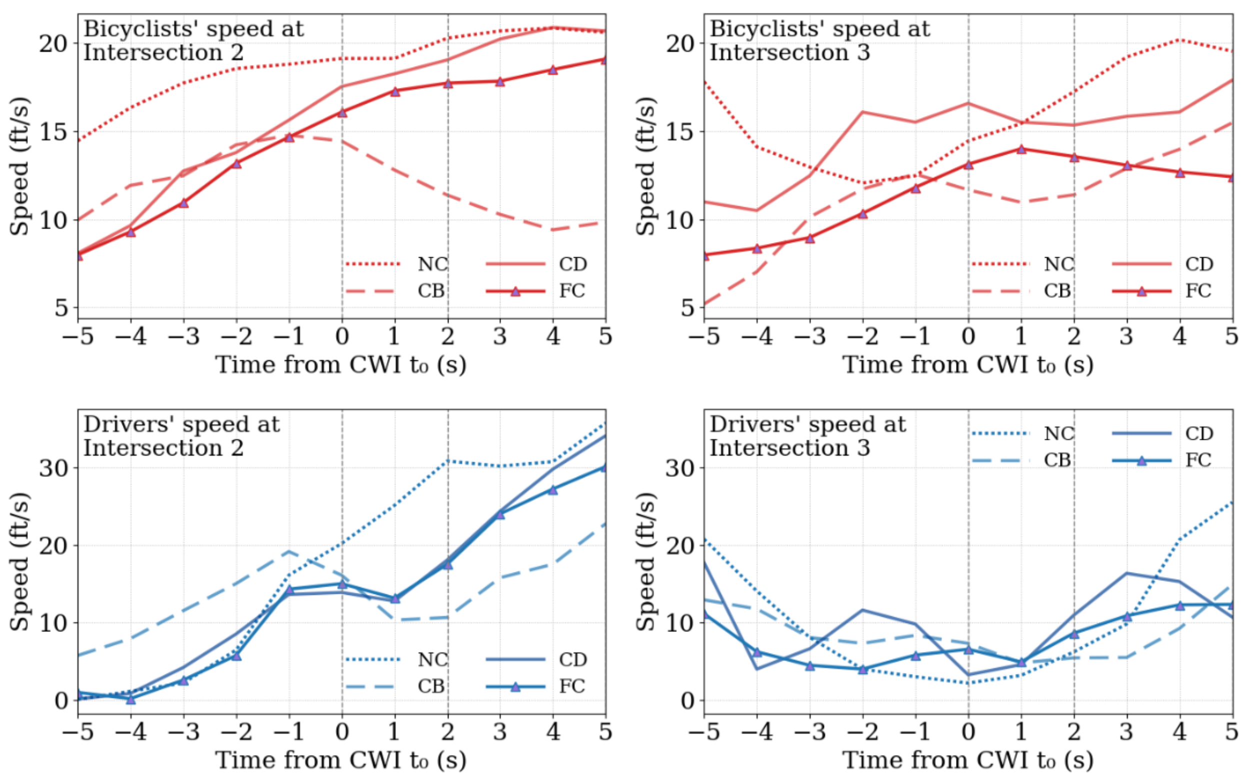


Figure 19: Impacts of CWI on bicyclists' and drivers' speed

Results from **Figure 19** show that, at Intersection 2, the two scenarios with 'Connected driver' yielded nearly identical driver's speed profiles, while the two 'Unconnected driver' scenarios revealed markedly different behaviors. In connected scenarios, drivers stop accelerating around the moment when CWI was provided (t = 0 sec) and, after a short reaction period (around t = 2 sec), began accelerating to pass through the intersection. In the NC scenario, drivers entered the conflict zone (t = 0 sec) at the highest speed compared to all other scenarios, maintaining the highest speeds at moment t = 2 sec. However, in CB scenario, drivers showed a different pattern: their speed decreased even before the moment of entering conflicting zone. This observation may be linked to bicyclist behavior in that scenario, highlighting the need to examine how the actions of one agent influence the others.

At Intersection 2, bicyclist behavior varied between the two ‘Connected bicyclist’ scenarios. In FC scenario, bicyclists maintained consistent acceleration. However, in the CB scenario, bicyclists exhibited a marked speed reduction, beginning even before CWI was triggered. They reached the lowest speeds of all scenarios at both t = 0 sec and t = 2 sec. This indicates that bicyclist speed choices in connected-bicyclist scenarios are shaped not only by CWI. On the other hand, in scenarios and bicyclist scenarios, speed profiles followed a more consistent pattern: in both cases, bicyclists accelerated steadily before t = 0 s, reached higher entry speeds compared to ‘Connected bicyclist’ scenarios, and continued accelerating afterward without clear evidence of speed adjustment.

Analyzing speed choices, CWI may not be the sole factor shaping bicyclists’ decisions. In contrast, the two “Connected driver” scenarios show no differences in speed profiles. However, further explanation is required to understand why the “Connected bicyclist” scenario produced different outcomes compared to the fully connected scenario for bicyclists and compared to the no-connectivity scenario for drivers. The CB scenario can be interpreted as follows: the bicyclist, who has the right of way, received CWI, while the unconnected driver accelerated into the intersection with the bicyclist in his blind spot. This created a more hazardous situation, forcing both users to stop accelerating. The bicyclist’s CWI reinforced their decision to decelerate, which in turn forced the driver to reduce speed even further. As a result, both users reached their lowest speeds at t = 2 sec compared to all other scenarios, creating a “dilemma situation.” Additionally, perception and anticipation measures help explain this outcome: bicyclists in the CB scenario reported lower perception scores than in FC, while drivers demonstrated lower anticipation compared to NC.

Finally, we examined whether behavioral adaptation (speed choice reduction) occurred across consecutive encounters. Drivers entered conflicting zones at Intersection 3 with lower speeds (at moment t = 0 sec) than at Intersection 2 across all scenarios, with only minor differences between connectivity conditions. Bicyclists also reduced entry speeds at Intersection 3, but to a lesser value. This contrast reflects their roles: drivers, required to yield, adapted more strongly, while bicyclists, with right-of-way, maintained steadier approaches.

Conclusions

This project introduced an integrated digital twin-based human-in-the-Loop simulation framework for evaluating the impacts of connectivity technologies on interactions between vehicles and vulnerable road users under realistic multimodal conditions. By tightly integrating PTV Vissim with the CARLA simulation platform, the study established a synchronized co-simulation environment that accurately replicated the Delaware Avenue corridor—a real-world multimodal arterial with mixed traffic operations. Within this virtual replica, human participants acted as drivers, bicyclists, and pedestrians, enabling controlled testing of the impacts of vehicle-to-pedestrian, vehicle-to-bicyclist, vehicle-to-infrastructure, and bicycle-to-infrastructure communication strategies in scenarios that closely mirrored real-world conflicts.

Two main experiment groups were conducted. The first evaluated V2P communication during right-turn-at-red scenarios involving aggressive driver behavior. Results showed that even basic auditory messages substantially improved pedestrian safety, eliminating collisions observed under non-communication conditions. Both partial and full communication increased yielding rates and enhanced pedestrian comfort, confirming that information sharing—whether indirect through infrastructure or direct from connected vehicles—promotes more cautious and confident decision-making. However, communication also induced a trade-off between safety and efficiency in short crossing windows, as participants often prioritized caution over crossing completion. These findings underscore the need to coordinate pedestrian signal timing policies with communication strategies to balance safety and operational efficiency.

The second experimental group focused on bicycle–vehicle conflicts under four connectivity configurations: no connectivity, driver-connected, bicyclist-connected, and fully connected. The designed interactions successfully reproduced Time-to-Collision (TTC < 2 sec) and Post-Encroachment Time (PET < 1.5 sec) events, validating the ability of the VR environment to generate realistic, measurable conflicts. Participants' physiological responses (elevated heart rate and skin conductance) and self-reported assessments confirmed that these events were perceived as stressful and unsafe, thus meeting traditional definitions of near-miss incidents.

Connectivity applications demonstrated distinct behavioral effects. Connected drivers exhibited higher perception and anticipation scores and reduced entry speeds at conflict zones, indicating improved situational awareness. Connected bicyclists, while benefiting from auditory Collision Warning Information, often adapted their speed in relation to driver behavior and contextual cues rather than CWI alone. The "bicyclist-connected" scenario produced a notable dilemma: even with the right of way, bicyclists slowed upon receiving CWI, prompting mutual deceleration and the lowest average speeds and highlighting the interdependence of users' behavioral adaptations in mixed-connectivity environments.

Behavioral adaptation across consecutive intersections further revealed that both drivers and bicyclists entered later conflicts more cautiously, particularly drivers who reduced approach speeds after prior exposure to critical events. This learning effect indicates that CWI not only influences immediate reactions but may also contribute to long-term behavioral adjustment in multimodal settings.

Overall, this project provides methodological and practical contributions. Methodologically, it demonstrates that digital twin-based dual-simulator frameworks can reproduce authentic conflict events and elicit genuine physiological responses, bridging the gap between traditional simulation and real-world observation. Practically, the findings support the integration of connected technologies into multimodal safety design, particularly in environments with complex driver-bicyclist-pedestrian interactions.

Future research should expand the participant pool to include broader demographic participation, additional VRU types, and various conflict typologies (e.g., overtaking or merging events). Moreover, integrating advanced data streams such as eye-tracking, reaction-time logging, and extended stress indices will further enhance understanding of how connectivity technologies influence human perception, decision-making, and safety performance within truly connected transportation systems.

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