Integrating Haptic Signals with V2X-based Safety Systems for Vulnerable Road Users

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***Abstract*—We study Vehicle to Everything (V2X)-based road traffic safety systems for Vulnerable Road Users (VRUs), particularly focusing on cyclists. The development of Advanced Driver Assistance Systems (ADAS) is usually first done with the help of computer simulation. For VRUs, this lacks suitable mobility models. Furthermore, real-world experimentation is often infeasible due to the immediate danger the test participants would be put into. As a solution, we propose a human-in-the-loop approach. We extended our Virtual Cycling Environment (VCE) to integrate a variety of signals to inform a cyclist riding a real bike on a training stand in a simulated 3D traffic scenario. A particular focus was put on haptic signals, which seem to be best suitable in complex traffic situations.**

***Index Terms*—Road Traffic Safety, V2X Communication, Simulation, Human-in-the-Loop, Haptic Signals**

I. Introduction

Safety for Vulnerable Road Users (VRUs), like cyclists, is still a major challenge and a substantial portion of all fatal traffic accidents involves cyclists. While the number and quality of Advanced Driver Assistance Systems (ADAS) for cars is increasing day by day, the amount of research on bicycle safety is significantly lower. Consequently, the integration of VRUs is very important. Cyclists need assistance systems tailored to their specific needs supporting them to recognize potentially dangerous situations and obstacles in their surrounding environment.

In the field of vehicular safety, there has been substantial progress, also thanks to modern communication systems [1]. ADAS for cars are now based on cooperative perception [2] taking into consideration not only the local sensors but exchanging relevant information with nearby cars, infrastructure, and even the cloud. Now, VRUs bring their own challenges as they are inherently focused on human behavior – corresponding research issues are investigated in the scope of Cyber Physical Social Systems (CPSSs) [3].

One of the main challenges integrating VRUs, in our case cyclists, with other vehicular safety systems is the communication of relevant events and the warning of the cyclists in case of critical situations. As mostly dangerous situations are to be examined, real-world outdoor experiments are extremely dangerous. However, realistic cycling behavior in simulations is still lacking. Therefore, human-in-the-loop simulation is a promising approach.

In this paper, we introduce an extension of our Virtual Cycling Environment (VCE) [4] to investigate a variety of signals to inform about possible dangers. This simulation environment enables realistic cycling behavior using a bike on a training stand and a Virtual Reality (VR) environment to enable the cyclist to move within a vehicular networking simulation. In a case study, we also assess the relevant latency components from sending warning messages to reception to reaction. For this, we developed a Collision Warning System (CWS) applicable together with different kinds of warning signals like visual signals (lights), auditory signals (sounds), and haptic signals (vibrations). Our CWS is based on Vehicle to Everything (V2X) communication to be able to early detect possible safety critical situations. Its effectiveness depends on whether there is an appropriate reaction of the cyclists to the given warning, i.e., the CWS and the reaction of the cyclists need intensive testing. Our main focus is on haptic signals, which we integrated in the handle bars of a real bicycle. We expect them to be less invasive and their influence on the visual and auditory perception of traffic to be low.

Our main contributions can be summarized as follows:

- We extend the VCE by implementing a CWS that conveys information to the cyclist via signals;
- we integrate haptic signals into the VCE by modifying the handle bars of the bike on the training stand; and
- we conduct two empirical experiments to evaluate the benefit of the visual, audio, and haptic warning signals.

II. Related Work

For cars, many different kinds of warning signals (including haptic ones) have been developed and tested with respect to their usefulness and influence on drivers [5]–[7]. However, the number of works on signals for bicycles for warning purposes is still limited; first projects make use of haptic signals for navigation, platooning, or collision warning [8]–[11].

The design of our haptic signals is partially motivated by the study by Matviienko et al. [12]. The authors examine children's understanding of different warning signals and the efficiency of combined signals in dangerous situations. The aim of their study was to investigate the effectiveness of different, single (unimodal) or combined (multimodal) stimuli. They came to the conclusion that the use of vibrations turns out to be suitable for giving directional cues. In another study, the authors also investigated bicycle navigation systems for children [9]. Both studies focus on the human-machine interaction rather than the integration with V2X-based safety systems.

Van Brummelen et al. [10] implemented a collision warning system for vehicles approaching a cyclist from behind by mounting vibration motors to each handle. Instead of using V2X to warn about approaching vehicles, their approach is based on a *single-beam laser rangefinder and two ultrasonic sensors that detect oncoming vehicles from behind*. The authors conclude that the system improved people's cycling behavior intuitively without impairing their concentration.

In another work, Céspedes et al. [11] used haptic signals to support cyclists moving in a platoon and combined cycling with cooperative driving. The system employs rotating cylinders in the handles for informing cyclists to speed up or slow down to attain a common speed. The authors found that the system improved cycling behavior without negatively affecting people's concentration.

In order to develop and test next-generation ADAS under safe and reproducible conditions, in earlier work, we developed the VCE [4]. The VCE integrates a physical bicycle into a virtual 3D environment that is coupled to the V2X simulator Veins [13]. In a proof-of-concept study on the potential safety gain by using V2X warning messages in an intersection scenario with a bicycle and a car, we found that when vehicles transmit periodic beacon messages (e.g., with a frequency of 10 Hz), the cyclist gains at least another 1 s until a collision occurs.

Later, Stratmann et al. [14] have shown the feasibility of the VCE for human-in-the-loop experiments, in particular with a focus on psychological effects. They conducted an experiment studying cyclists' visual attention capacity under various traffic conditions.

We build upon these findings and integrate a variety of signals into the VCE for empirical studies of VRU safety systems. As a proof of concept, we evaluated the latency components of a V2X-based CWS.

III. V2X FOR VULNERABLE ROAD USERS

Information exchange between a car and a VRU involves the interaction of different components, and each of them induces often non-negligible delays. Figure 1 shows the overall architecture of the cooperative mobile system. Latencies related to information exchange are introduced for gathering relevant positioning information in conjunction with small processing delays at the car denoted as $t_{\text{car-proc}}$; for transmitting and receiving that particular information over the wireless channel denoted as t_{comm}; for processing the received information on the receiving side denoted as $t_{\text{bike-proc}}$; and for the user reacting to the information denoted as t_{reaction}. In this section, we focus on the communication delay t_{comm} for network communication.

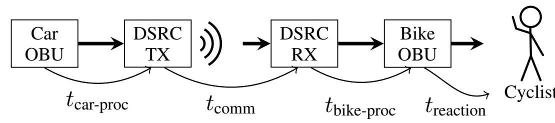

Figure 1. System overview of a cooperative safety system for VRUs. The latencies $t_{\text{car-proc}}$, t_{comm}, $t_{\text{bike-proc}}$, and t_{reaction} represent the delays to expect from the system for local processing delays at the car, to transmit this information to the VRU, to process the information on the bike, and finally to cognitively process and react to a signal.

In the following, we focus on IEEE 802.11p [15] as a V2X communication protocol. IEEE 802.11p uses an OFDM PHY with 10 MHz channel bandwidth. This relates to PHY timing parameters $T_{\text{preamble}} = 32\,\mu\text{s}$, $T_{\text{signal}} = 8\,\mu\text{s}$, and $T_{\text{sym}} = 8\,\mu\text{s}$. Similarly, we use MAC parameters according to the standard as $t_{\text{SIFS}} = 32\,\mu\text{s}$, $t_{\text{slot}} = 13\,\mu\text{s}$. Further, we assume broadcast-only communication (thus, not requiring any acknowledgements), which has been found beneficial for vehicular communications [16] and assume the sender operating in Outside the Context of BSS (OCB) mode using Access Category AC_BE with AIFSN=6 slots and a minimum contention window of $CW_{\text{min}} = 15$. The calculation of the time for transmitting data is based on the PLME-TXTIME.confirm primitive outlined in the standard. When transmitting headers and payload of size n bits at 6 Mbit/s ($N_{\text{DBPS}} = 48\,\text{bit}$), this time can be calculated as

$$t_{\text{tx}}(n) = T_{\text{preamble}} + T_{\text{signal}} + \left\lceil \frac{16 + n + 6}{N_{\text{DBPS}}} \right\rceil \cdot T_{\text{sym}}. \quad (1)$$

For a broadcast frame with a typical payload of $n = 300\,\text{B}$, we calculate $t_{\text{tx}}(2400) = 448\,\mu\text{s}$. This time can be achieved, if the channel has already been idle for some time and the transmission was performed immediately (no blocked MAC queues).

If we now take channel access time into consideration and focus on the case when the channel just became idle, we derive for the Access Category AC_BE

$$t_{\text{AIFS}} = t_{\text{SIFS}} + 6 \cdot t_{\text{slot}} = 110\,\mu\text{s} \quad (2)$$

and consequently for transmitting a broadcast frame taking backoff times into account

$$t_{\text{tx-MAC}}(n) = t_{\text{comm}} = t_{\text{AIFS}} + \mathcal{U}(0, CW_{\text{min}}) \cdot t_{\text{slot}} + t_{\text{tx}}(n). \quad (3)$$

In the worst case, when the random variable $\mathcal{U}(0, CW_{\text{min}})$ yields CW_{min} (in our case 15 slots), the time for transmitting a frame of 300 B takes up to $t_{\text{tx-MAC}}(2400) = 753\,\mu\text{s}$.

Of course, we also have to investigate delays induced by upper layers, e.g., the network protocol. State of the art beaconing protocols require each vehicle periodically broadcasting information about its current state including the position, velocity, and acceleration. A typical example is the European standard for vehicular communication ETSI ITS-G5 [17]. Such beaconing protocols usually assume a maximum beacon interval of 1 s.

Thus, the worst case delay for beacon transmission incorporating a maximum beaconing interval of 1 s yields $t_{\text{worst}} = 2\,\text{s} + t_{\text{tx-MAC}}(n) + t_{\text{prop}}$, where t_{prop} denotes the propagation delay of the wireless signal. This worst case delay occurs when a beacon with outdated positioning information has just been handed to the hardware to be scheduled for transmission and new positioning information is available directly after scheduling the transmission where this new positioning information cannot be integrated in the beacon to be transmitted.

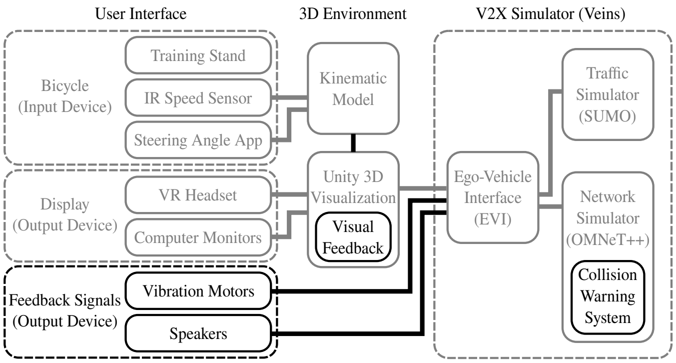

Figure 2. Extended architecture of the VCE with the newly added Collision Warning System (CWS) and signals (highlighted in black). Signals are provided to the cyclist via vibration motors (haptic), speakers (audio), or a virtual display in the Unity 3D visualization (visual). Collisions detected by the CWS are forwarded to the signals via the EVI.

IV. Virtual Cycling Environment

A. Overview

The Virtual Cycling Environment (VCE) [4] allows to cycle within a virtual 3D environment on a physical bicycle on a training stand. Using sensors attached to the bicycle, realistic bicycle movement can be achieved within the virtual environment for studying the cyclists' behavior. This allows researchers to perform human-in-the-loop experiments to test future ADAS in safe and reproducible conditions. An overview of the VCE is shown in Figure 2. The system can be separated into three main parts: (1) A user interface, (2) a 3D simulation environment, and (3) the V2X simulator.

The user interface consists of a physical bicycle which is fixed in a training stand and equipped with sensors. The sensor data is processed by a kinematics model, which outputs a realistic bicycle movement that is used for the visualization and the V2X simulator. The corresponding virtual bicycle is called the ego vehicle.

The ego vehicle as well as the virtual world (i.e., the road network, buildings, and other road traffic participants) are visualized with corresponding 3D models in Unity. The road network and the position of buildings can be based on map data exported from OpenStreetMap. In order to allow interaction between the ego vehicle and the virtual world (e.g., other traffic participants), the visualization is coupled to the V2X simulator. The coupling between the real-time visualization and the time-discrete V2X simulator is done by the EVI [18]. It integrates the ego vehicle into the road traffic simulator, which also simulates all other road traffic participants.

Veins [13] is used to simulate realistic and standard compliant V2X communication between all simulated road traffic participants. For this, the EVI sends the position of the ego vehicle and all fellow vehicles also to the network simulator. Based on the simulated V2X communication (e.g., Cooperative Awareness Message (CAM) beaconing), it is possible to implement various cooperative safety applications.

The simulated behavior of the ego vehicle and the fellow vehicles as well as the virtual world is shown to the cyclist via a display serving as output device. This can be either computer monitors or a VR headset (e.g., a HTC Vive), which can enhance immersion into the virtual environment.

B. Adding (Haptic) Warning Signals

Cyclists should receive directional cues in dangerous traffic situations to assist them in avoiding crashes. The cyclist should be able to understand the warning cues intuitively and be assisted without much additional cognitive load. We extended the VCE to study different warning signals for cyclists in case of an imminent collision. We further added software to detect collisions in the vehicular networking simulator and signaling devices to warn the cyclist. The new VCE modules are depicted in Figure 2.

For the CWS, for each vehicle in a set radius, the algorithm computes the current position of the vehicle in relation to the cyclist. Based on the direction of movement, it is computed whether both paths will intersect. If so, the algorithm calculates the Time-To-Collision (TTC) for both vehicles. Obviously, if the TTC for both vehicles is equal, they will collide if no further action is taken. We use the principle of Post-Encroachement-Time (PET) [19] to provide warnings in sufficiently dangerous situations (estimated collisions as well as close misses). If more than one potential dangerous situation is detected, the most immediate one is selected.

Warnings generated by the CWS are sent to the EVI in the next synchronization step. As an artifact of the time-discrete behavior of the V2X simulator, this process can take up to 100 ms. The EVI forwards the received events to the signaling devices to warn the cyclist. First measurements show that this takes less than 100 ms. All these delays are included in $t_{\text{bike-proc}}$.

We implemented three different signaling devices: (1) Vibration motors in the handle bars for haptic signals, (2) speakers emitting warning sounds for audio signals, and (3) a virtual display on the bike in the 3D visualization for visual signals. Haptic and audio signaling is controlled by a Raspberry Pi connected to the EVI, while the virtual display signal is directly integrated into the 3D visualization.

Haptic signals are transmitted to the cyclist via vibrations on the handlebar. We installed flat shaftles smartphone motors embedded in a foam cushion on the handlebar of the bike, as shown in Figure 3 (bottom right). The foam cushion keeps the vibration signal local to the handle which allows the cyclist to distinguish between left and right signals. It also avoids cyclist's discomfort due to the motors pressing into the palms of their hands during experiments. The motors are driven directly by the Raspberry Pi over GPIO as they only require an operating voltage of 2.5–3.5 V. The vibration happens at a frequency of about 200 Hz with an acceleration of around 7.4 m/s^2, which is in line with the psychophysical characteristics of the sense of touch [20]. This results in a robust, comfortable, and inexpensive haptic signaling device that can deliver vibration signals directly to the hands of the cyclist. For the audio signal, we use stereo speakers playing a beeping noise on the selected side. The visual signal consists of two red LEDs positioned on each side of the handlebar.

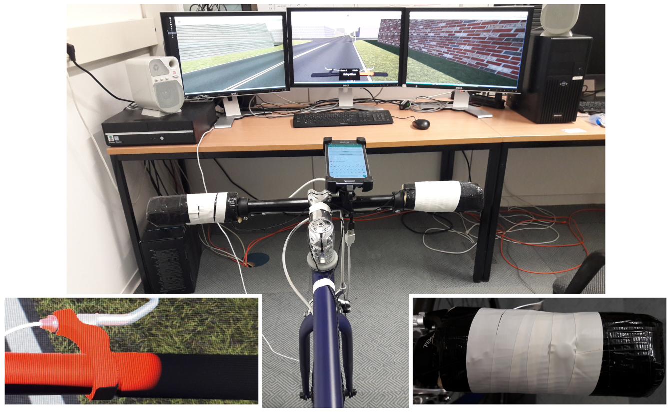

Figure 3. Experiment setup with bicycle and running 3d visualization. The sub pictures show the visual signal (left) and a vibration motor (right).

To reduce the need for additional hardware, we designed a virtual display for visual warnings in the 3D visualization (cf. Figure 3, bottom left).

V. Proof-of-Concept and Evaluation

We conducted a set of experiments to assess the usability of the developed toolkit. The main objective is to show that it can readily be used for large-scale empirical experiments covering both the technical development of novel ADAS and V2X communication protocols as well as the psychological understanding of cyclists' behavior in complex traffic situations.

A. Setup

Figure 3 shows the setup for the experiments. The immersiveness of the virtual environment is supported by the monitor setup creating a wider field of view [21]. As a result, the participant has an improved realistic overview of traffic situations by having an extended field of view to the left and to the right. We used monitors instead of 3D glasses in order to reduce the risk of motion sickness during the experiment.

Warnings were signalled to the participants as described in Section IV-B. Two vibration motors were installed on the physical bicycle. For the audio signal, two speakers were positioned on the monitor desk with one speaker on each side. The visual signals were presented to the cyclist via the virtual display in the Unity 3D visualization.

B. Empirical Experiments

In a first step, we evaluated the influence of (haptic) signals on the reaction time of a cyclist in dangerous situations in comparison to no signal support. Secondly, we compared different kinds of signals (*haptic*, *visual*, and *audio*) to find the best one for a potential real life application. In both cases, we observe how and how fast cyclists react to a warning signal by measuring their reaction time for coming to a stop within 3 s after a warning has been (or would have been) sent. We define the reaction time as the interval between raising a signal and the point in time when the negative acceleration exceeds a threshold of $4\,\mathrm{m/s^2}$. This definition allowed us to compare actions like stopping after a warning signal to e.g., merely slowing down. For the sake of brevity, we omit such comparisons in the following analysis.

In our experiments, we followed the within-participants design, i.e., rather than splitting the participants into one group for each condition, we obtain data for conditions from each participant. The benefit of this approach is the possibility to observe differences in conditions for individuals, which might not otherwise emerge in a between-participants design with the same number of participants due to their different cycling styles. Predictability is a further important consideration. A naive implementation for a cyclist model would let the simulated cyclist react the same way to any warning of approaching vehicles at consecutive intersections. A human cyclist, however, would soon anticipate the danger and approach the following intersections more slowly than before. We tried to mitigate this by randomizing the timing of intersecting cars as well as by alternating between junctions with and without traffic.

Furthermore, we varied the number of cars at each intersection between a number of 1 to 3 to add another factor of surprise. Whenever there was traffic, one of three scenarios randomly takes place: The traffic is coming from the left and driving straight ahead, the traffic is coming from the right and driving straight ahead, or the traffic is coming from the right and turning left. These were chosen based on typical dangerous urban scenarios [22].

For the first part, we had 17 voluntary participants, with 4 of them female and 13 male aged between 17 and 56 years. For the second part, we invited the same participants and had a total number of 15 voluntary participants with 5 of them female and 11 male aged between 22 and 57 years. Two participants had to be switched. The experiments were approved by the ethics committee of Paderborn University and are in accordance with the principles of the *Declaration of Helsinki*.

The procedure for each of our participants was as follows. Each person started by reading and signing a declaration of consent. Afterwards, the meaning of each type of warning signal was explained and participants were encouraged to behave as in real traffic, to avoid collisions, and to follow the arrow signs. In preparation for the haptic signals, each possible vibration (left, right, and both) was demonstrated before the experiment. A short traffic-free tutorial level gave the participant an opportunity to get familiar with the VCE. In our experiments, we group levels into blocks. After each block, a (short) break takes place to restore the concentration of the participants.

To gain further knowledge about the participants' opinion of the signals, we developed two questionnaires (cf. Table I showing sample questions), which the participants answered after doing the experiments. In the questionnaires, six different topics are evaluated, including participant demographics, as well as regarding the warning system, understandability, acceptance, distraction, general questions, and feedback. All questions could either be answered by choosing an answer on a 5-point Likert scale or by writing a text answer (for feedback).

Table I
RESPONSES TO QUESTIONNAIRES WITH LIKERT SCALE FROM 1 TO 5

Question	M_{Haptic}	SD_{Haptic}	M_{Audio}	SD_{Audio}	M_{Visual}	SD_{Visual}
1. Understandability (incomprehensible … completely understandable)	4.47	0.80	3.94	1.18	3.31	1.45
2. Distinguishability (very difficult … very easy)	3.47	1.07	3.63	1.20	4.00	1.20
3. Acceptance on own bicycle? (not at all … absolutely)	3.29	1.05	2.34	1.15	2.31	1.30
4. Acceptance of friends on their bicycle? (not at all … absolutely)	3.18	0.73	2.38	1.20	2.25	1.00
5. Distractiveness (very distracting … not distracting at all)	3.94	0.77	2.88	1.15	2.75	1.13
6. Intuitiveness (very intuitive … not intuitive at all)	1.82	2.34	2.19	1.05	3.19	1.17
7. Timing (too late … too early)	2.53	0.8	2.50	0.82	2.69	0.48
8. Helpful in identifying dangerous situations (not at all … absolutely)	2.71	1.05	2.88	1.09	2.44	0.81
9. Helpful for prevention of accidents in real life (not at all … absolutely)	3.88	0.86	3.25	1.13	2.75	1.06

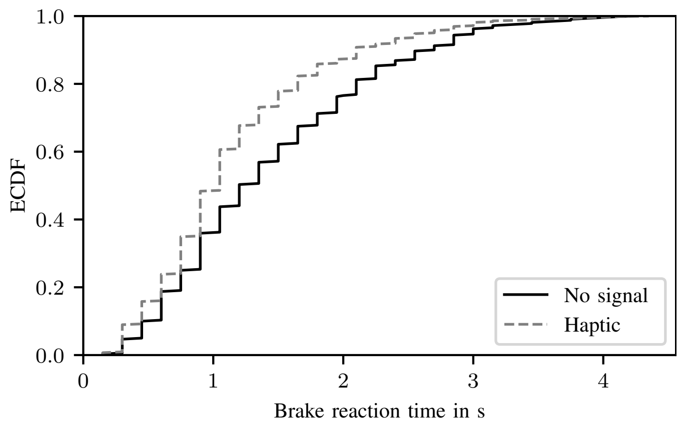

Figure 4. ECDFs of reaction times comparing the use of haptic to no signaling

C. Results

During the experiments, we collected data on the number of collisions with other vehicles as well as the current speed of the bicyle with a sampling frequency of 7 Hz. This data is granular enough for predicting the moment of first reaction and thereby the reaction time. If a warning was received by the bicycle, it was identified whether the cyclist came to a stop within the following 3 s.

In our first experiment, the mean reaction time $M_{\text{allbraking}}$ measured for braking is 1.2 s with and 1.48 s without haptic signaling. To evaluate the results in more detail, we conducted an independent-samples t-test, comparing participants' reaction times with and without the support of haptic signals. As shown in Figure 4, reaction times were significantly lower with haptic signals activated than without ($t(630.4) = 4.80,\ p < 0.001$). The total number of braking actions in this experiment was 744; the distance between steps in Figure 4 is therefore largely due to the sampling frequency of 7 Hz.

Focusing on the data of individual participants, we find that 9 participants reacted faster with haptic support, 6 participants' reactions did not change, and one participant was slower. During the first experiment, 25 accidents took place, 8 with and 17 without haptic signals.

In the following experiment, we compared the different types of signal types. We observed no significant change in reaction times for the different signals. Overall, the reaction time was 1.4 s for audio signals ($SD = 0.73\,\text{s}$), 1.39 s for visual signals ($SD = 0.75\,\text{s}$), and 1.28 s for haptic signals ($SD = 0.75\,\text{s}$).

However, this changes when each participant is investigated individually. Comparing the reaction time with haptic signals to audio signals, 6 participants reacted faster with haptic, 8 were equally fast, and one was slower. Comparing haptic signals to visual signals leads to the same results. Additionally, while using audio signals in comparison to visual ones, 5 participants reacted faster, 7 equally, and one participant slower. While the number of collisions using audio (4) or haptic signals (6) is quite similar, this number is significantly higher for visual signals (13).

In addition to the collected speed data, the two questionnaires for the different signals had to be evaluated. As can be seen in Table I, haptic signals were rated best in understandability and acceptance on a real bicycle. Participants thought haptic signals to be much less distracting and a little more intuitive. Additionally, participants believed them to be most helpful in real life. Visual signals were rated as most distinguishable. However, during the experiment, participants confused the visual signals with indicators to turn left or right.

VI. CONCLUSIONS

In this paper, we presented an extension for our Virtual Cycling Environment (VCE) to study Advanced Driver Assistance System (ADAS) for cyclists in a semi-realistic environment. In particular, we integrated different kinds of signals with a focus on haptics to convey information about an approaching danger to the cyclist. As a proof-of-concept, we implemented a Collision Warning System (CWS). In a set of empirical experiments, we compared reactions with haptic signals to no signals and haptic signals to audio and visual ones. We used our extended VCE to investigate the effectiveness of the signals in reducing the reaction time and avoiding accidents. Even for this rather simplistic experiment, we see that haptic signals improved the reaction time in comparison to no warning and reduced the number of accidents. No significant difference could be measured for the other signals, though visual signals lead to more accidents. Overall, participants liked haptic signals best and rated them as potentially most helpful in real life: easily understandable and least distracting.

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