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Safety Performance Assessment via Virtual Simulation of V2X Warning Triggers to Cyclists with Models Created from Real-World Testing

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Abstract: The overall crash statistics in the EU still show a very significant number of car–cyclist crashes. Within the Horizon 2020 project Safe-Up, countermeasures have been developed to reduce this number. One of these countermeasures involves a V2X-enhanced on-board unit for cycles, which can provide on-time warning triggers. The research assumption was based on studying the benefits of connectivity in enhancing cyclists' safety. This study assessed the performance of this potential technology both qualitatively by analyzing volunteer feedback during physical testing and quantitatively by virtual simulations. The volunteers' study showed positive findings on system's safety relevance, user experience, and user acceptance. The method applied for the virtual simulation is a prospective safety performance assessment with reconstructed accident scenarios based on the GIDAS database and cyclist behavior models, obtained from physical testing. The results using a warning trigger 4 s prior to the collision showed a potential safety benefit of approximately 98%. It should be noted that this trigger time was found to be quite early in both physical testing and virtual simulation. Further research is required to evaluate the system's performance in more complex urban scenarios, as well as to design the human–machine interaction strategies for optimal accident avoidance.

Keywords: safety performance assessment; V2X; GIDAS; cyclists' safety; traffic safety; accident avoidance

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1. Introduction

1.1. Accident Statistics

The crash statistics in Europe still show a significant amount of 4.3 cyclist fatalities per million inhabitants [1]. Almost half of the total accidents in Europe still involve vulnerable road users [2], especially in urban areas, where the number of crashes is very high. Trends in Germany show an increase of cyclists' accidents from ~95,000 in 2019 to ~106,000 accidents in 2022 [3]. The share of pedelec rider accidents (electric drive support to 25 kph) increased to almost 30% in 2022. Due to the high amount of vulnerable road user and cyclist collisions resulting in severe injuries, research on collision causation is performed heavily. In [4], an injury severity prediction of cyclist collisions has been performed, resulting in a multitude of parameters responsible for high severity collisions.

1.2. C-ITS Benefit for Safety

The safety potential of the Connected Intelligent Transport System (C-ITS) technology in future road traffic ecosystems has been recognized both on technological and policy levels by the European Commission. In compliance with the technological framework, the final report of the C-ITS platform highlights that collaborative perception of vulnerable road users (VRUs) and drivers/vehicles is expected to harvest the expected safety benefits of C-ITS implementation, ensuring interoperability and fast deployment [5]. From the policy perspective, the update of the EU Road Safety Policy Framework 2021–2030 [6] identifies that connectivity is expected to demonstrate tremendous road safety potential, which is in line with the recent recommendation by the EU Commissioner for Mobility and Transport that future initiatives should focus on the exploration of new technologies that will "allow vehicles to 'talk' to each other, to the road infrastructure, and to other road users" [7]. C-ITS safety benefit is further supported by the industry through the recently launched coalition of 19 leading innovators from the automotive, bicycle, and technology sectors who agreed on collaborating towards enhancing safety for cyclists and e-bike riders on North American roads by deploying V2X technologies. This includes improving physical infrastructure for safer cycling and implementing timely safety alerts to reduce crashes through digital visibility between bicycles and cars [8].

1.3. V2X Technology Introduction

The most important responsibility of any ITS station that participates in a vehicle-to-anything (V2X) ecosystem is the periodic transmission of cooperative awareness messages (CAM) with a rate of 1 to 10 Hz, broadcasting information, that, among other things, contains the type, the position, the motion dynamics (speed, heading, acceleration, etc.), the state (for example, if the accelerator or the brake is active) of the station, and much more useful information. Therefore, a station capable of receiving this kind of message immediately becomes aware of all connected (transmitting CAMs) stations in radio frequency (RF) range [9]. A local dynamic map (LDM) of these connected stations (vehicles and other transmitting ITS stations) in range can be constantly maintained during operation and updated by the received CAM messages. Most modern vehicles come with a variety of installed perception sensors (cameras, radars, lidars, etc.) that, in case of a detected collision emergency, can trigger a driver warning or even collision avoidance or emergency braking systems. The "vision capabilities" of these sensors can be severely weakened due to physical obstructions, especially in urban contexts. V2X communication can play the role of an additional perception sensor, remedying in a way, the perception "blindness" due to occlusions. However, little research has been conducted on investigating the integration of cyclists (and vulnerable road users in general) into connected accident prevention technologies [10,11], as well as how efficiently wireless networks can contribute to cyclists' accident risk reduction [12–15].

1.4. Study Context and Correlation to Project "Safe-Up"

The EU Horizon project initiative "Safe-Up" addressed traffic accidents by developing new safety technologies with a special focus on cyclist collisions and the integration of other traffic participants and vehicles into the accident prevention cascade. One of these technologies was an on-board unit for cycles, which warns the cyclists based on V2X-information from roadside units or cars [16]. In our conducted real experiments, the virtual vehicle with its predefined route had no way to react to any imminent danger. The sole responsible for avoiding action, was the cyclist and only after the system's on-time warning triggered, since the vehicle was not physically visible to the cyclist. The potential benefits in terms of reduced severity or overall occurrence of crashes were analyzed through a virtual safety performance assessment. The reaction of cyclists to a warning signal were considered by a cyclist model, which was created based on real physical testing data. The virtual test scenarios were reconstructed accidents taken from the GIDAS database.

1.5. Contribution to Sustainability

This study makes significant contributions to sustainability, aligning well with the United Nations Sustainable Development Goals (SDGs) for 2030 [17]. The focal point of the study is the C-ITS cyclists' safety technology, aiming to enhance cyclist safety through real-time two-way communication to prevent accidents and reduce fatalities and serious injuries. This directly contributes to UN Goal 3 on Good Health and Well-Being, promoting societal sustainability. Moreover, the study advocates for the adoption of bicycles as a safe and efficient mode of transportation, endorsing healthier and more eco-friendly commuting options. In this direction, the study aligns with UN Goal 13 by reducing the overreliance on traditional vehicles, consequently mitigating carbon emissions and air pollution. Lastly, through the developed innovation that falls under Goal 9 on Industry, Innovation, and Infrastructure, the study supports the development of resilient infrastructure and smart transportation solutions, fostering sustainable urban mobility in line with UN Goal 11.

2. Materials and Methods

2.1. V2X System Technology and Physical Testing Setup

A prototype on-board unit (OBU) device with, among other features, V2X communication capabilities, was designed and installed on a commercial electric cycle (Kona Dew-E manufactured by Kona Bicycles, Ferndale, WA, USA). This OBU incorporated all the necessary hardware and software modules to facilitate ITS-G5 V2X communications, including the transmission and reception of ETSI standardized CAM messages. The device's precise location is determined using a high-performance positioning engine with a multi-band Global Navigation Satellite System (GNSS) receiver, in combination with an inertial measurement unit that, in addition to its own accelerometer, gyroscope, and magnetometer sensors, can also utilize the GNSS receiver signals to provide enhanced positioning results via its own fusion engine.

The cycle had some pre-installed hardware features provided by the manufacturer. It came equipped with a common bike computer that accumulates real-time information about the bike's status, including current speed (via a Hall sensor installed on the back wheel), current cadence (measured via the electric motor's controller), battery status, and more. This bike computer was connected with the OBU device via BLE (Bluetooth Low Energy), making all the cycle's real-time information available to the OBU. To obtain the brake status of the cycle, which was not initially available, the team installed Hall sensors in both the front and back brake levers. These brake sensors were directly connected (via a wired connection) to the OBU, enabling real-time monitoring of the brake status. In addition to enhancing awareness, the brake status was essentially used as a trigger for measuring cyclists' reactions after an emitted warning.

Furthermore, the cycle was also equipped with a touch LCD display, where the cyclist was informed about sensor outputs (positioning, speed, heading, battery status). Using this human–machine interaction (HMI) element, the user could also interact with the device, by starting and stopping on-demand its operation, for better control over the experiments. There were also visuals on the screen that presented collision warnings (Figure 1) and were accompanied with an acoustic buzzer sound in the case of a collision detection, so that the cyclist could become aware of potentially dangerous situations as fast as possible after the detection from the system, without having to keep his gaze constantly on the screen, in order to take avoiding action.

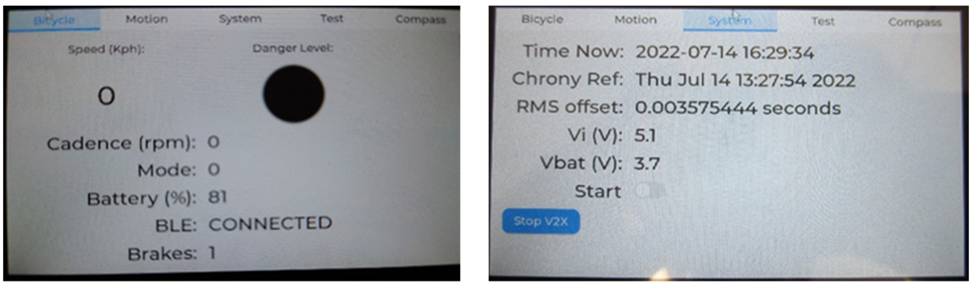

Figure 1. HMI screens on cycle's LCD display.

The key features of the OBU enhanced cycle are summarized below:

- Short range communications with V2X ITS-G5;
- Localization via multiband GNSS receiver fused with IMU;
- Real-time monitoring of speed, brake and cadence;
- Basic visual and acoustic interaction with the rider via LCD display and a buzzer respectively.

To fully exploit the enhancements on the cycle and evaluate the actual performance of the developed system, realistic riding behavior from a real cyclist on a cycle, who could react to warnings as a human would, was deemed necessary. The physical testing was conducted with 12 volunteers at an IDIADA proving ground in Santa Oliva, Spain. The testing scenarios were based on the findings of the accidentology study conducted in [1] and characterized within [16] to fit Euro NCAP testing protocols and physical testing requirements. For safety reasons, using a real vehicle in scenarios with a high probability of collision between the vehicle and a real cyclist was not feasible. Therefore, a virtual vehicle was used instead. The term "virtual vehicle" refers to a V2X device station that transmitted a pre-recorded series of CAM messages, precisely corresponding to the vehicle's path, speed, and direction for the scenario being tested in each run. With this strategy, in the V2X ecosystem, the vehicle was "present" without posing any collision safety risks during the experiments. The volunteers riding the cycle were instructed to follow predefined paths and speeds that corresponded to the chosen scenario being tested each time. Figure 2 shows the setup of the physical testing environment.

Figure 2. (**left**): OBU physical test device; (**right**): physical testing of V2X system in the user study.

The selected metric for triggering the warning was time-to-collision (TTC). A threshold of four (4) seconds was adapted as the TTC that triggers a "lighter" cyclist warning, corresponding to an orange indication on the LCD display and a threshold of two (2) seconds for a "stronger" warning, corresponding to red indication on the screen. In both warning cases, however, the buzzer sound was also triggered. A typical V2X application latency timing is the time period between the "birth" of data from sensors of a transmitting ITS station (time at which the transmitted sensor data are available), until this information is received, processed, and interpreted into a meaningful user warning at the receiving ITS station and must be less than 300 milliseconds in case of transport safety applications [18–20]. This latency is highly affected by the "freshness" of sensor data, station's hardware capabilities and computational resources, software and application algorithm efficiency regarding processing time, and finally HMI response time. The minimum TTC needs also to consider the user (in our case, rider) reaction time, containing the human perception and interpretation of the HMI information, as well as the human action upon the emitted warning, the time needed by the bicycle to physically perform the rider's intentions (brake the bicycle), plus finally an error margin compensating mainly for possible positioning inaccuracies. The 2 s stronger warning (~1.7 s for user perception and action based on the above explanation) was selected as the minimum time that could enable collision avoidance and is consistent, for example, with Euro NCAP recommendations [21] where points are awarded when a forward collision warning is issued at a TTC equal or greater than 1.7 s. Furthermore, previous research by the authors [22] about rider reaction times in a motorcycle simulator after HMI stimulus provided similar results. The lighter warning of 4 s was selected in order to compensate for user unfamiliarity with the experiment scene and the enhanced bike itself. Especially, the installed V2X antennas in the steering could make even an experienced rider a little uncomfortable at first. In a real-world road environment, a 4 s TTC warning will probably lead to alerts even in cases where the rider is perfectly aware and in control of the situation. On the other hand, it will also enable a more comfortable reaction and manoeuvre from the recipient of the warning.

2.2. Volunteers' Survey during Physical Testing

A survey was conducted to gather feedback from the volunteers who participated in the cyclist safety testing phase. In total, 12 surveys were collected, with an equal number of responses from the volunteers. Due to confidentiality restrictions of the testing facility (IDIADA Euro NCAP proving ground), it was only allowed to recruit IDIADA personnel. The volunteers selected were not involved in the specific study and related project developments. Although the statistical sample was very small and not representative of demographics and diversification aspects, the survey purpose was to perform an initial analysis of key human factors related aspects that should be explored with wider audience in the future. Nevertheless, previous experience and research assisted towards this direction [23]. The design of the study was based on the FESTA methodology [24], and was structured into two sections:

1. Briefing section: This section was completed by the volunteers before the actual test. It included general questions about the volunteers' familiarity with the V2X technology and detailed explanations of the testing scenarios tailored to the real testing environment.
2. Debriefing section: This section was completed by the volunteers after the completion of the test. It contained questions related to system performance, perceived safety, timing and type of warnings, and other relevant factors.

2.3. Prospective Safety Performance Assessment

The Prospective Safety Performance Assessment method is described in [25]. The overall goal is an early assessment of the potential benefit of a (safety) technology to the increase in road safety in terms of reduction of crash occurrence or injury severity.

2.4. Evaluation Scope and Research Question

The evaluation scope was the potential benefit assessment of a V2X-capable cycle on-board unit triggering a warning signal to the cyclist in a potential collision scenario, which represented crossing right, crossing left, and car turning left with cyclist in same direction scenes (Figure 3). These scenes have been defined in "Safe-Up" project [1] since they represent a majority of crash scenes in accident databases and additionally are not yet fully covered by EuroNCAP.

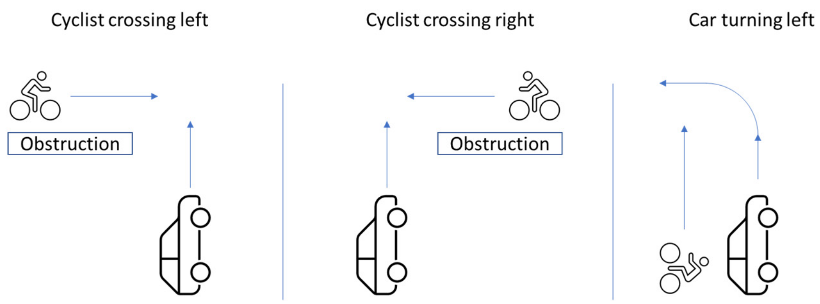

Figure 3. Assessed scenes for the Safety Performance Assessment.

The following slightly modified research question was finally derived for the assessment in "Safe-Up" project [16]:

"What is the safety benefit of a VRU C-ITS warning system on connected cyclists in supporting them to mitigate safety-critical events with passenger cars, triggered by a radio signal based (OBU, VRU-smart device) communication and detection system, in terms of accident avoidance compared to Car to VRU collisions on urban roads?"

The idea behind this research question is a quantitative comparison of accidents in urban roads that happened over the last years in German cities to a potential integration of a cyclist communication device, which triggers a warning signal to a cyclist.

2.5. Baseline Generation

Based on GIDAS-PCM data, 1345 reconstructed real-world accidents were prepared for a simulation in IPG CarMaker "version 10.2". These scenarios consist of two traffic participants and reconstructed objects/occlusions; see Figure 4.

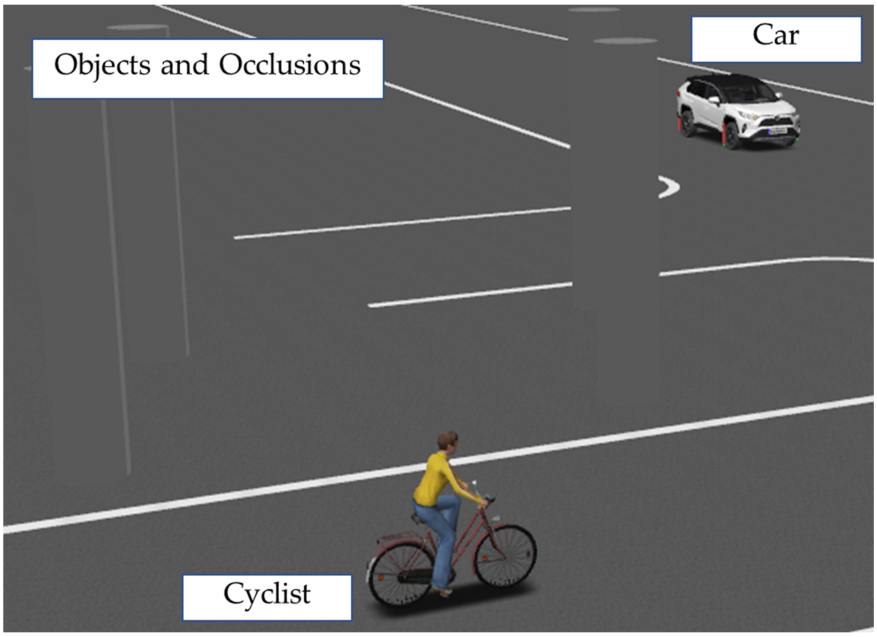

Figure 4. Overview PCM data-based simulation in IPG CarMaker.

2.6. Cyclist Model Generation

The safety benefit assessment is investigating the ability of a cyclist to prevent a collision when receiving a warning signal. To assess such kinds of behavior, a model is needed in simulation which represents a typical cyclist behavior. A wide range of behavioral models can be used in simulation, such as mathematical models describing the trajectory and decisions made of an agent [26] and more sophisticated models trying to model human cognition and interactions with the environment [27]. In Safe-Up, physical tests with real cyclists were performed in three different scenes, as depicted in Figure 3, to assess the reaction of cyclists to a warning signal. The measured trajectories were used to create a mathematical model for typical reaction times to a warning trigger at t = 0 s and the resulting brake distance and acceleration. Due to the scenario-based approach of the available GIDAS scenarios and the event-based triggering of the cyclist, this kind of model was seen to be sufficient for the performance assessment in this study.

Figure 5 shows all cyclists' velocities over time in the three assessed scenarios. The reaction was similar in all scenes to the warning trigger. The horizontal part of the curves represents the reaction time to the warning trigger, whereas the pitched part represents the continuous braking and thus constant deceleration of the cyclist to a standstill.

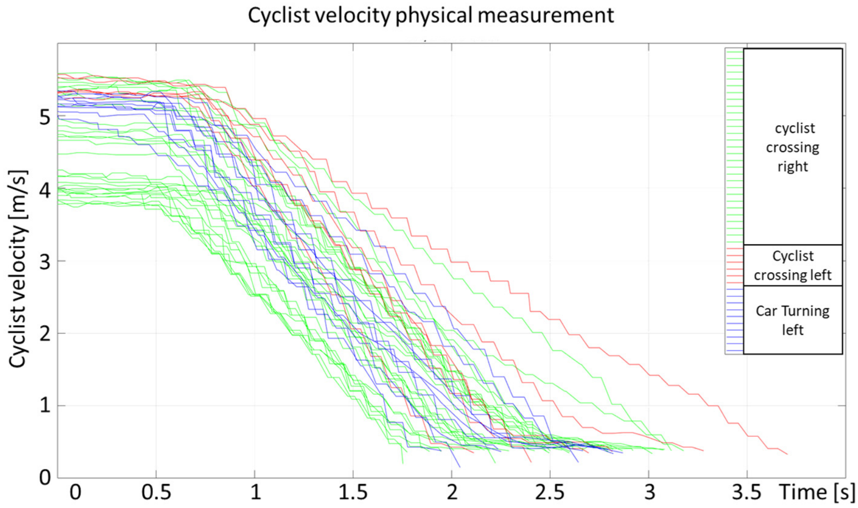

Figure 5. Cyclist velocity in physical measurements and different scenes.

Assuming a normal distribution for each of the two segments of the curve (reaction time and acceleration), the behavioral distribution can be computed and assessed. A 90% probability range coverage leads to the following min. and max. distribution values (see Table 1), which have been used as cyclist model parameters. The lower bound of this range (high negative acceleration and small reaction time) is classified as the "progressive" driver, which reacts early to a warning trigger and brakes hard. As an opposite, the upper bound is classified as the "defensive" driver, someone who takes longer to react to a warning trigger and decelerates less progressively. These two types of models may not represent individual driver reactions anymore but can be used to assess the majority of cyclists' behaviors and the effect of safety technologies in simulation. Thus, a reasonable range of driver behavior characteristics can be shown and tested in simulation.

Table 1. Gathered min. (defensive profile) and max. (progressive profile) distributions, representing the 90%tile.

Cyclist Type	Acceleration [m/s^2]	Reaction Time [s]
"progressive"	−3.6	0.37
"defensive"	−2.0	0.71

Based on these results, a functional mock-up unit (FMU) can be created, which is then deployed in the virtual simulation, see Figure 6. The unit works the way that the initial path of the cyclist is followed in the beginning of the simulation. As soon as the warning trigger is sent, the cyclist will react and overrule the given trajectory with the defined behavior.

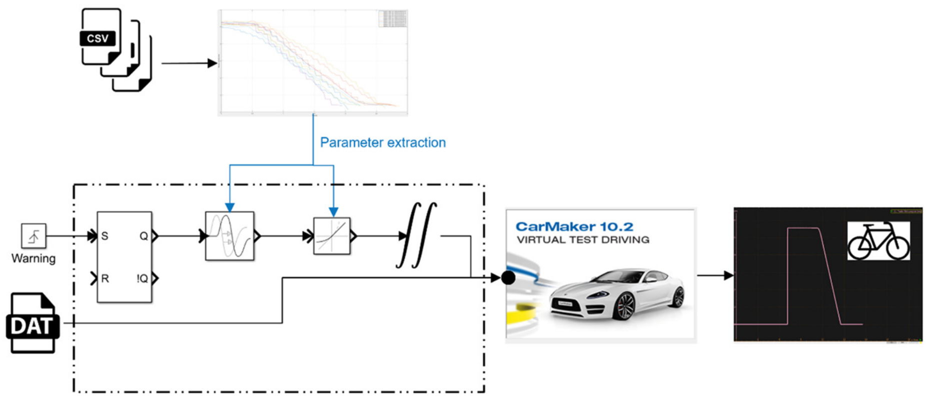

Figure 6. FMU concept for cyclist model integration.

3. Results

3.1. Volunteers' Feedback during Physical Testing

A survey was conducted with the 12 volunteers who participated in the physical tests of the cyclists' safety system. The volunteers were recruited from the hosting facility personnel with the condition of not being involved in the specific study nor the "Safe-Up" project itself. Their feedback is relevant to understanding the human acceptance next to the physical assessment in virtual simulation. Among these volunteers, 10 were males and 2 were females, whereas 3 fell in the age range of 18–24 years old; 8 were in the age group of 25–39 years old and 1 volunteer between the ages of 40–59. Due to the restrictions in effect in the Euro NCAP testing facility, a balance on demographic representation was not feasible.

The key observations derived from the analysis of the volunteers' feedback on the survey are presented in the following paragraphs.

Out of the 12 volunteers, 9 expressed familiarity with V2X technology and were subsequently questioned about their opinion regarding its potential safety benefits in enhancing road safety. The results, as illustrated in Figure 7 below, indicate that all responders believe that V2X technology has the potential to contribute to road safety enhancement.

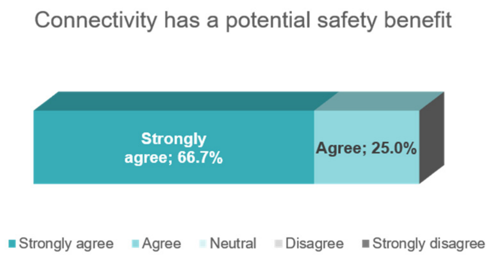

Figure 7. Volunteers' opinion on the safety benefit of V2X technology.

With regards to the relevance of the type of information that the system can provide to the cyclists while they are cycling in an urban area, the majority of the volunteers indicated that real-time information on vehicle location, what the vehicle detects, and what it is doing or about to do, is either necessary or good to know, as shown in Figure 8. Only a small percentage of respondents believed that such information is not as crucial. Three volunteers mentioned other types of information that they consider vital for cyclists, such as information related to crash avoidance and the provision of information via acoustic messages instead of visual information.

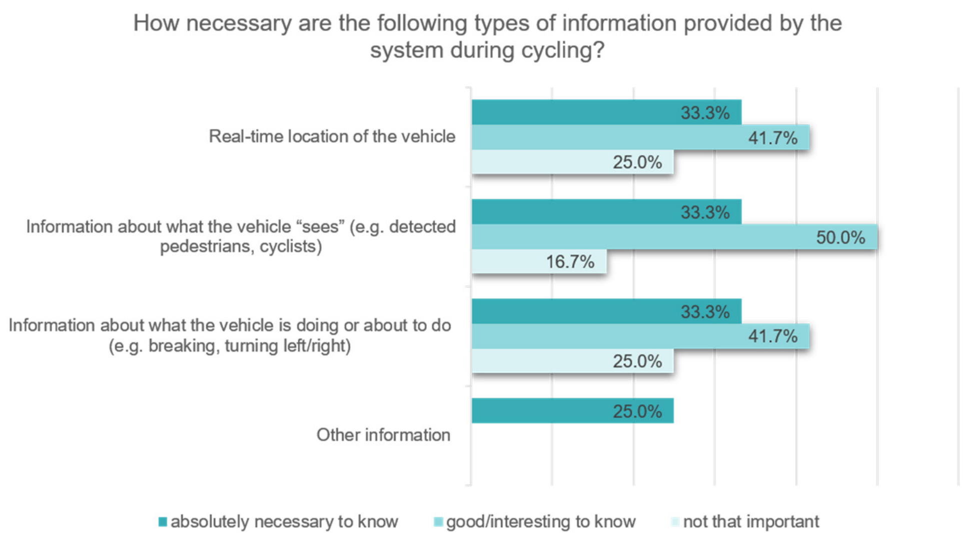

Figure 8. Relevance of the type of information the system can provide to the cyclist while cycling.

The next question addressed to the volunteers pertained to the evaluation of the system's usage in a real-world environment, focused on aspects such as ease of use, safety, usefulness, excitement, and overall user experience. Based on the findings depicted in Figure 9 below, we can draw the conclusion that the majority of the volunteers agreed that if the system was operational in a real-world context, it would be easy to use, safe, useful, pleasant, and a positive experience for the cyclist. Nevertheless, it is worth noting that two respondents expressed the belief that the system usage might be too complex in a realistic urban context.

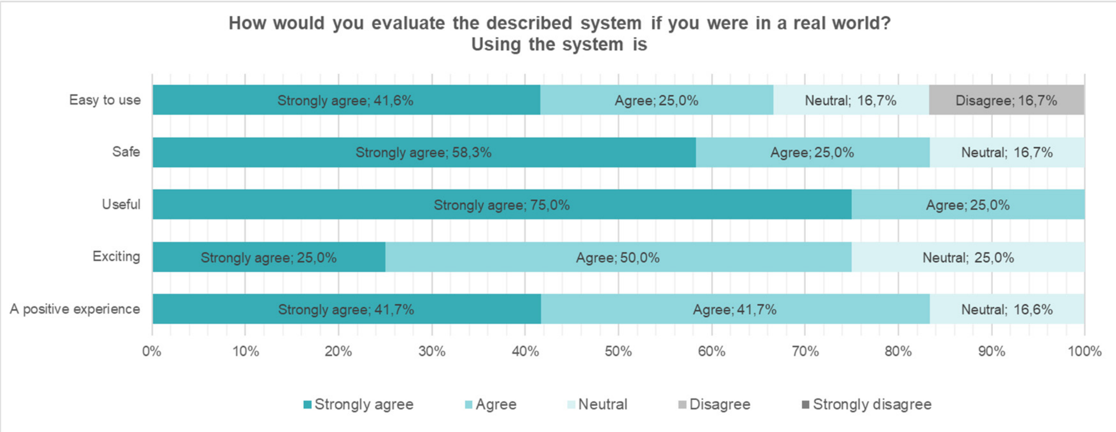

Figure 9. System usage evaluation in a real-world environment.

Concerning the timing of the warnings triggered by the system, the volunteers indicated that during the testing phase, the warnings were provided relatively early, as depicted in Figure 10. This observation was also confirmed in the virtual simulations and is further elaborated upon in the Discussion section.

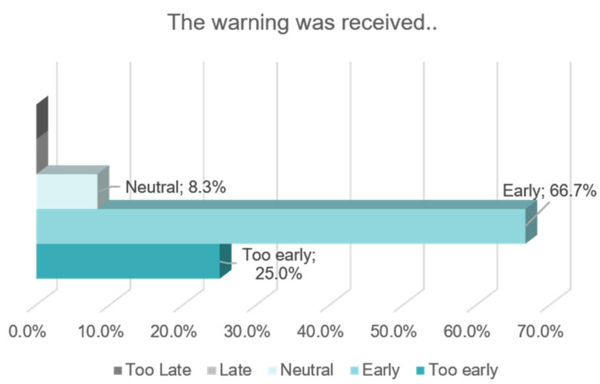

Figure 10. Evaluation of the system warning time.

Although the development of a holistic human–machine interface (HMI) design for the safe interaction of the system with cyclists was not within the scope of this research, and only a basic HMI was deployed for the purposes of the testing phase as presented in Section 2.1, it was essential for future research to sense the volunteers' preferences on the type of communication elements, or combinations of them, they believe would be effective, perceivable, and safe for a commercially marketed system. The proposed HMI elements and their combinations have been thoroughly studied by the authors in previous research [23].

Based on the results summarized in Figure 11 below, it can be concluded that elements integrated into the cyclist's helmet, such as vibration (9 out of 12 volunteers) and audio (8 out of 12 volunteers) were the most popular amongst the volunteers. Vibration on the cyclist's smartwatch was selected by 5 volunteers, while audio on the smartphone (3 out of 12 volunteers) and visual information (2 out of 12 volunteers) attracted less popularity. It is also worth noting that three volunteers proposed combinations of elements that include: (a) audio and vibration on both the smartphone and smartwatch) and (b) auditory communication on the helmet and vibration on the smartwatch.

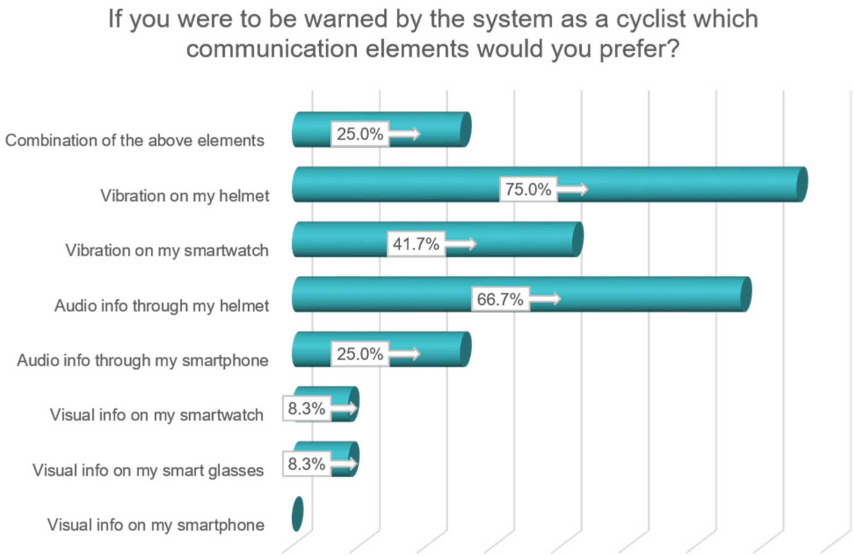

Figure 11. Volunteers' preferences on types of communication elements for a cyclists' safety system.

Furthermore, the volunteers' attitude toward their willingness to use such a system if it were available in the market was assessed. In total, as shown in Figure 12, 11 volunteers indicated that they would be willing to use the system if it became available, while one volunteer had a neutral opinion.

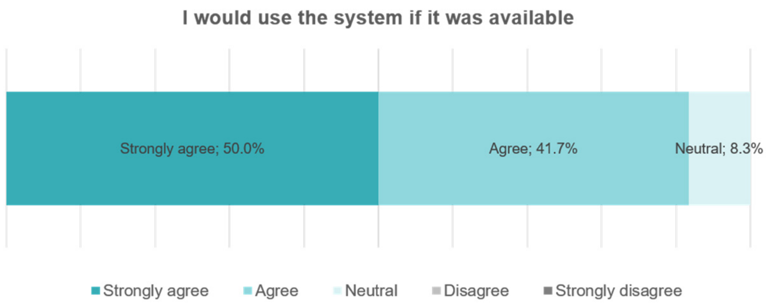

Figure 12. Attitude towards system willingness to use if it was available in the market.

At the conclusion of the survey, the respondents were asked for suggestions regarding the future user-centred development of the system. The feedback received included recommendations such as the improvement of the crash algorithm, the creation of a user manual for safe operation, and the preference of vibration over acoustic or visual elements for more effective communication with the cyclist.

3.2. Baseline Simulation Results

Overall, 1345 PCM cases were simulated in IPG Carmaker. All scenarios led to a crash between cyclist and passenger car. Figure 13 shows the distribution of the assessed crash scenarios. In total, 6% have been car turning left cases, 44% cyclist crossing left, and 50% cyclist crossing right cases. The scenarios also included occlusion elements, which reduce visibility between cyclist and passenger car (sight obstructions).

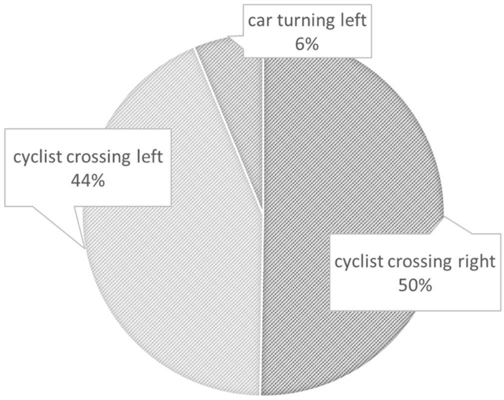

Figure 13. Distribution of crash scenarios in PCM data.

3.3. Treatment Simulation Results

The treatment simulation included the applied treatment technology. In this simulation study, only the bicyclist was equipped with the C-ITS, whereas the vehicle was not enhanced by any safety technology. It was assumed that an on-board unit would be capable of providing early warning triggers to the cyclist, which are received by the cyclist, in the case of a collision prediction, 4 s before a collision. Two different types of cyclist models react to this warning signal with a specific delay and deceleration signal, as described in Table 1.

From 1345 crash cases, there were 24 remaining collisions for the "progressive" and 25 crash cases for the "defensive" cyclist behavior model. In all other simulation cases, the warning trigger led to a cyclist being able to stop in time before a collision occurred. Figure 14 shows an overview of exemplary simulation cases, where the cyclist was able to stop in time and prevent a collision with the passenger car. The remaining distance to the vehicle mainly depended on the type of braking profile of the cyclist—which is, in these cases, a progressive profile. This warning trigger was based on a time to collision (TTC) prediction between cyclist and vehicle; with higher velocities of cyclist and vehicle, the remaining distance between the two opponents increased (see middle left picture).

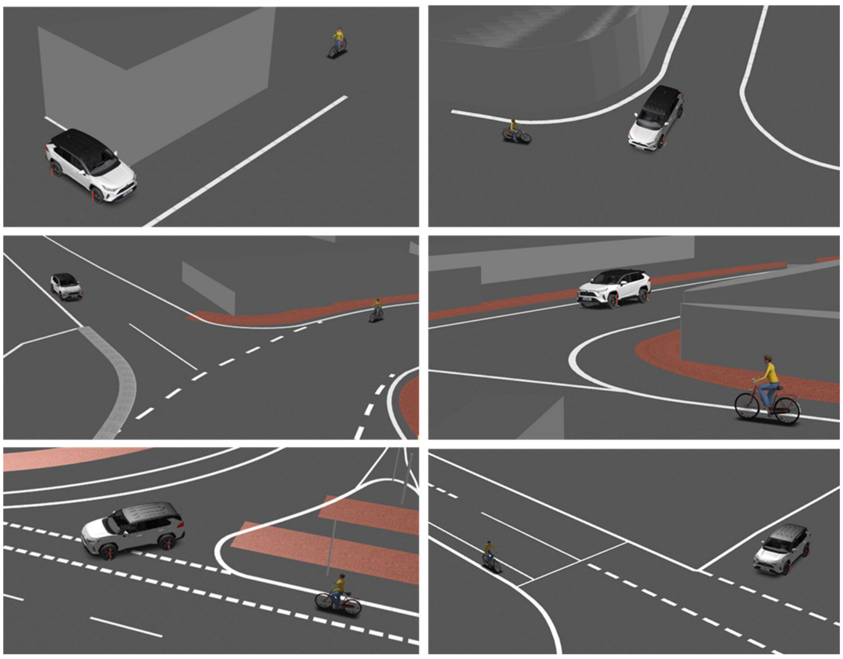

Figure 14. Overview avoided collisions by progressive cyclists at the time of standstill.

The remaining crash cases can be clustered in three different causation models.

1. Cases where the cyclist was already in a standstill position from the beginning of the computer simulation and the opponent vehicle did not prevent the crash. In some cases, especially the vehicle turning cases, the vehicle was travelling, but the cyclist not. Naturally, a collision is not avoidable;
2. Cases where the cyclist got a warning trigger, but its trajectory was very near the vehicle trajectory. The cyclist stopped on the vehicle trajectory;
3. Cases where the trigger to the cyclist came very late, due to vehicle acceleration almost in front of the collision and thus a TTC already below 1 s.

An example for causation model Nr. 3 is depicted in Figure 15. Displayed is a car tuning left case and a cyclist travelling in same direction. At the time of turning, indication with a true collision prediction value of the system the TTC value was already at 0.82 s. The cyclist was not able to stop in time and prevent a collision.

Figure 15. Car turning left case at the time of VRU warning trigger.

3.4. Safety Performance

The Safety Performance of the VRU warning system can be calculated as:

$$\Delta f = \frac{f_{Treatment}}{f_{Baseline}} - 1, \quad (1)$$

with f being the number of collision cases for either the baseline scenarios or the treatment scenarios.

For the "progressive" cyclist model, a reduction of crashes by −98.2% and −98.1%, respectively, for the "defensive" cyclist was achieved.

4. Discussion

4.1. Virtual Simulation

This paper presented a way to include safety technologies for cyclists into the virtual simulation and assessment of safety performance. The most common simulation frameworks and tools are mainly constructed to assess safety and technology benefits from the vehicle perspective. The models included here can now support a vehicle-only technology or cyclist-only technology assessment and, in future research, it would also be possible to assess implications and benefits of two similar technologies applied on vehicles and cyclists simultaneously or even in a collaborative way.

The limitations of the simulation should be considered and are as follows:

1. See: The used sensor models represent an ideal perception and thus ideal object lists. The world-model knows the position of all objects in the scene;
2. Think: The trajectory prediction and TTC calculation is based on ideal object data. The model itself includes a trajectory-prediction algorithm. The on-time-warning trigger is set to 4 s;

3. Act: The vehicle model itself is strictly following the defined trajectory. The cyclist model will always react to this warning trigger with a defined delay and constant deceleration, which are based on the described test data.

Overall, it can be stated that the simulation depicts an idealized system. However, using ideal perception systems in virtual performance analysis is a common practice in research and industry, especially when the focus is on the assessment of functions and algorithms; in this case, the warning trigger time sufficiency and the general applicability of the applied algorithm. Closed loop simulation with highly accurate perception and sensor models are not yet state of the art, due to the high amount of calculation power and time consumption. The transfer of the gathered data to real-world performance will shift the benefit values due to errors in perception though.

4.2. Safety Function and User Experience

The virtual simulation was used to assess and test a V2X-based warning trigger to cyclists. The safety benefit of 98% shows huge potential of this system in the assessed reconstructed accident scenarios.

The defined trigger time of 4 s seems to be too early for some of the simulations as can be seen in Figure 16. In this scenario setting, where there are just 2 traffic participants, the distance to the conflict location is 20 m for the cyclist and 55 m for the car. It is, therefore, difficult for the cyclist to associate the vehicle as a conflict partner with the trigger signal. Furthermore, in more complex traffic situations, the allocation of the corresponding traffic object will be more difficult, even for a human being. This corresponds to the findings of the physical trail, see Figure 10. Thus, further research and assessment on early warnings is needed.

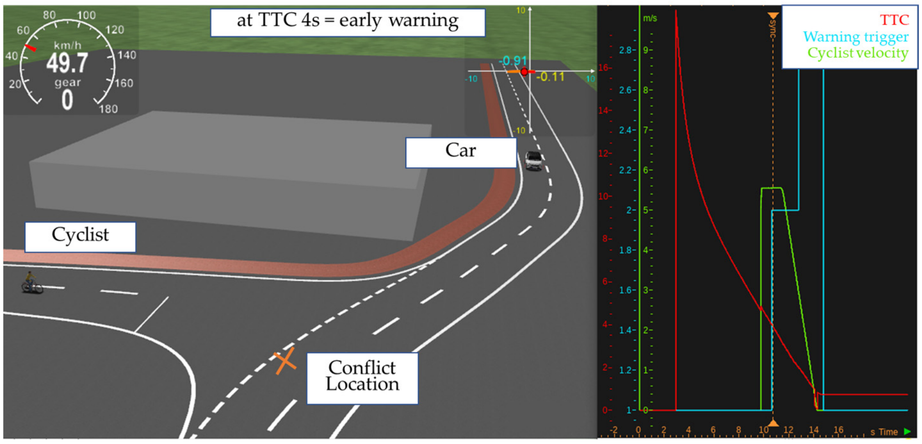

Figure 16. PCM scenario at TTC 4 s.

In terms of the future perspective of the shown V2X system, additional experiments involving a higher statistical sample of real users are necessary to more accurately adjust the warning time, balancing between avoiding early warnings, and providing sufficient time actions that can prevent imminent collisions [16,28]. On top, different types of bicyclists' behavior (i.e., aggressive cycling), as performed in [29], could be also investigated.

Moreover, in real urban environments, the number of road users is significantly higher. Therefore, the TTC threshold used in the real experiments, which involved only one vehicle and one cyclist, to trigger the cyclist warnings, might lead to a significant increase in false positives—a situation where the system was falsely triggered. The assessment of false positives would require also non-collision scenarios, which are not available in the used dataset. Detecting and tracking multiple cyclists simultaneously might affect V2X systems' capability and such limitations are, to date, underexplored [29].

Finally, it should be noted that human–machine interface (HMI)-related issues were not within the scope of this study, but it also needs to be stated that HMI studies with cyclists in general are very rare and the initial findings of this study can already provide insights on where to focus research in future (e.g., vibration-based communication). Consequently, interaction strategies, as well as their effectiveness on human perception of the situation, are topics for future research. Nonetheless, the feedback collected from the volunteers during the physical tests regarding the type of communication will be used in future research. These human factors studies are anticipated to contribute to the overall assessment of a future deployed system [16,29].

5. Conclusions

This paper presented a way to include physical test results into virtual simulation processes to better describe the human behavior in simulations. The derived simulation model is simplistic but sufficient to assess the principal feasibility of warning triggers to a cyclist and the ability to prevent collisions. Enhancing the simulation process and the model quality in terms of behavioral aspects will further support such assessments. Furthermore, future studies should also focus on the design of appropriate interaction strategies based on different safety-related scenarios to both enhance systems' performance and ensure cyclists' perception and awareness of the situation [23].

Currently, the main V2X use cases focus on vehicle technology enhancement, as shown in [30–32]. This technology applied on vehicles alone will most probably not solve the Vision 0 (zero traffic casualties) of the European Union. Additional technologies need to be developed, which will provide a significant contribution to this vision and a sustainable mobility. Within this paper, a volunteer-based survey on real-world testing, as well as a virtual performance assessment of V2X-enhanced on-board unit on cycles were conducted. The survey produced positive results on the perceived safety benefit and on the user acceptance of the technology. The virtual performance assessment also concluded that the potential safety benefit of an V2X-enhanced OBU on cycles is significant and that this technology could contribute a lot to the reduction of traffic casualties The study results have shown that a V2X-based cyclist safety system can tremendously impact accident avoidance. However, further research is required to develop a robust system and evaluate the system's performance in more complex urban scenarios, as well as to assess users' experience and perception through user-centred studies.

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References

1. Balint, A.; Labenski, V.; Schories, L.; Huertas Leyva, P.; Ostling, M.; Schmidt, D.; Schindler, R. D2.6 Use Case Definitions and Initial Safety-Critical Scenarios, Safe-Up EU Project. 2022. Available online: https://www.safe-up.eu/s/SAFE-UP_D26_Use-case-definitions-and-initial-safety-critical-scenarios.pdf (accessed on 16 October 2023).
2. Olszewski, P.; Szagała, P.; Rabczenko, D.; Zielińska, A. Investigating safety of vulnerable road users in selected EU countries. *J. Saf. Res.* **2019**, *68*, 49–57. [CrossRef] [PubMed]

3. Destatis.de. Persons Involved in Accidents Causing Personal Injury by Type of Traffic Participation. Available online: https://www.destatis.de/EN/Themes/Society-Environment/Traffic-Accidents/Tables/drivers-pedestrians.html (accessed on 12 July 2023).
4. Scarano, A.; Riccardi, M.R.; Mauriello, F.; D'Agostino, C.; Pasquino, N.; Montella, A. Injury severity prediction of cyclist crashes using random forests and random parameters logit models. *Accid. Anal. Prev.* **2023**, *192*, 107275. [CrossRef] [PubMed]
5. European Commission. C-ITS Platform Phase II: Final Report. 2017. Available online: https://transport.ec.europa.eu/system/files/2017-09/2017-09-c-its-platform-final-report.pdf (accessed on 23 October 2023).
6. European Commission. *EU Road Safety Policy Framework 2021–2030—Next Steps towards 'Vision Zero'*; Publications Office of the European Union: Luxembourg, 2020.
7. European Commission. Road Safety: New Rules Clear Way for Clean, Connected and Automated Mobility on EU Roads. 2021. Available online: https://ec.europa.eu/commission/presscorner/detail/en/IP_19_1648 (accessed on 23 October 2023).
8. Winograd, T.; Auto, Cycling and Tech Innovators Launch Coalition for Cyclist Safety Based on V2X Deployments. Bosch Media Service, Press Release 23 October 2023. Available online: https://www.bosch-presse.de/pressportal/de/en/auto-cycling-and-tech-innovators-launch-coalition-for-cyclist-safety-based-on-v2x-deployments-259136.html (accessed on 4 December 2023).
9. Sjoberg, K.; Andres, P.; Buburuzan, T.; Brakemeier, A. Cooperative Intelligent Transport Systems in Europe: Current Deployment Status and Outlook. *IEEE Veh. Technol. Mag.* **2017**, *12*, 89–97. [CrossRef]
10. Lim, K.L.; Whitehead, J.; Jia, D.; Zheng, Z. State of data platforms for connected vehicles and infrastructures. *Commun. Transp. Res.* **2021**, *1*, 100013. [CrossRef]
11. Kapousizis, G.; Ulak, M.B.; Geurs, K.; Havinga, P.J.M. A review of state-of-the-art bicycle technologies affecting cycling safety: Level of smartness and technology readiness. *Transp. Rev.* **2023**, *43*, 430–452. [CrossRef]
12. Nourbakhshrezaei, A.; Jadidi, M.; Sohn, G. Improving Cyclists' Safety Using Intelligent Situational Awareness System. *Sustainability* **2023**, *15*, 2866. [CrossRef]
13. Scholliers, J.; van Sambeek, M.; Moerman, K. Integration of vulnerable road users in cooperative ITS systems. *Eur. Transp. Res. Rev.* **2017**, *9*, 15. [CrossRef]
14. Arena, F.; Pau, G.; Severino, A. V2X Communications Applied to Safety of Pedestrians and Vehicles. *J. Sens. Actuator Netw.* **2020**, *9*, 3. [CrossRef]
15. Zoghlami, C.; Kacimi, R.; Dhaou, R. 5G-enabled V2X Communications for Vulnerable Road Users Safety Applications: A Review. *Wirel. Netw.* **2022**, *29*, 1237–1267. [CrossRef]
16. Nikolaou, S.; Castells, J.; Lorente Mallada, J.; Gragkopoulos, I.; Tsetsinas, I. D3.7 Demo 4 System for On-Time Warning Provisions to VRUs and Drivers in Critical Conditions Update, Safe-Up Eu Project. 2022. Available online: https://www.safe-up.eu/s/SAFE-UP_D37_-Demo-4-system-for-on-time-warning-provisions-to-VRUs-and-drivers-in-critical-conditions.pdf (accessed on 30 November 2023).
17. United Nations. General Assembly Resolution A/RES/70/1. Transforming Our World, the 2030 Agenda for Sustainable Development. 2015. Available online: https://documents-dds-ny.un.org/doc/UNDOC/GEN/N15/291/89/PDF/N1529189.pdf?OpenElement (accessed on 5 December 2023).
18. ETSI (European Telecommunications Standards Institute). Intelligent Transport Systems (ITS); V2X Applications; Part 1: Road Hazard Signalling (RHS) Application Requirements Specification. 2013. ETSI TS 101 539-1 (V1.1.1). Sophia Antipolis Cedex—France. Available online: https://www.etsi.org/deliver/etsi_ts/101500_101599/10153901/01.01.01_60/ts_10153901v010101p.pdf (accessed on 5 December 2023).
19. ETSI (European Telecommunications Standards Institute). Intelligent Transport Systems (ITS); V2X Applications; Part 2: Intersection Collision Risk Warning (ICRW) Application Requirements Specification. 2018. ETSI TS 101 539-2 (V1.1.1). Sophia Antipolis Cedex—France. Available online: https://www.etsi.org/deliver/etsi_ts/101500_101599/10153902/01.01.01_60/ts_10153902v010101p.pdf (accessed on 5 December 2023).
20. ETSI (European Telecommunications Standards Institute). Intelligent Transport Systems (ITS); V2X Applications; Part 3: Longitudinal Collision Risk Warning (LCRW) Application Requirements Specification. 2013. ETSI TS 101 539-3 (V1.1.1). Sophia Antipolis Cedex—France. Available online: https://www.etsi.org/deliver/etsi_ts/101500_101599/10153903/01.01.01_60/ts_10153903v010101p.pdf (accessed on 5 December 2023).
21. Assessment Protocol—Vulnerable Road User Protection, Euro NCAP, v.10.0.5, December 2021. Available online: https://cdn.euroncap.com/media/67553/euro-ncap-assessment-protocol-vru-v1005.pdf (accessed on 4 December 2023).
22. Symeonidis, I.; Dimokas, N.; Gragopoulos, I.; Tsetsinas, I.; Chrysochoou, E.; Touliou, K.; Valenti, G.; Biral, F.; Gemou, M.; Bekiaris, E. SAFESTRIP: Hardware in the Loop Motorcycle Simulator Experiment for C-ITS applications. In Proceedings of the 13th International Motorcycle Conference of the ifz, Cologne, Germany, 1 September–6 October 2020.
23. Diederichs, J.P.F.; Fontana, M.; Bencini, M.; Nikolaou, S.; Montanari, R.; Spadoni, A.; Widlroither, H.; Baldanzini, N. New HMI Concept for Motorcycles—The Saferider Approach. In *Engineering Psychology and Cognitive Ergonomics, Lecture Notes in Computer Science, Proceedings of the EPCE 2009, San Diego, CA, USA, 19–24 July 2009*; Harris, D., Ed.; Springer: Berlin/Heidelberg, Germany, 2009; Volume 5639, pp. 358–366.
24. European Commission. Connected and Automated Driving Knowledge Base: FESTA Handbook Version 8. 2023. Available online: https://www.connectedautomateddriving.eu/wp-content/uploads/2021/09/FESTA-Handbook-Version-8.pdf (accessed on 30 November 2023).

25. *ISO/TR 21934-1:2021*; Prospective Safety Performance Assessment of Pre-Crash Technology by Virtual Simulation. ISO (International Organization for Standardization): Vernier, Switzerland, 2021.
26. Ma, X.; Luo, D. Modeling cyclist acceleration process for bicycle traffic simulation using naturalistic data. *Transp. Res. Part F Traffic Psychol. Behav.* **2016**, *40*, 130–144. [CrossRef]
27. Fonseca, L. Simulation-based evaluation of a generic autonomous emergency braking system using a cognitive pedestrian behaviour model. In Proceedings of the 27th Enhanced Safety of Vehicles (ESV), Conference, Yokohama, Japan, 3–6 April 2023.
28. Sewalkar, P.; Seitz, J. Vehicle-to-Pedestrian Communication for Vulnerable Road Users: Survey, Design Considerations, and Challenges. *Sensors* **2019**, *19*, 358. [CrossRef] [PubMed]
29. Zhou, D.; Chang, M.; Gu, G.; Sun, X.; Xu, H.; Wang, W.; Wang, T. Analysis of Risky Driving Behavior of Urban Electric Bicycle Drivers for Improving Safety. *Sustainability* **2022**, *14*, 1243. [CrossRef]
30. Koukounaris, A.I.; Stephanedes, Y.J. Connected Intelligent Transportation System Model to Minimize Societal Cost of Travel in Urban Networks. *Sustainability* **2023**, *15*, 15383. [CrossRef]
31. Feifel, H.; Erdem, B.; Menzel, D.M.; Gee, R. Reducing Fatalities in Road crashes in Japan, Germany, and USA with V2X-enhanced-ADAS. In Proceedings of the 27th Enhanced Safety of Vehicles (ESV), Conference, Yokohama, Japan, 3–6 April 2023.
32. Kabil, A.; Rabieh, K.; Kaleem, F.; Azer, M.A. Vehicle to Pedestrian Systems: Survey, Challenges and Recent Trends. *IEEE Access* **2022**, *10*, 123981–123994. [CrossRef]