Invited Paper: Safety Assistance Systems for Bicyclists: Toward Empirical Studies of the Dooring Problem

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ABSTRACT

To reach the goal of zero traffic fatalities a year, one building block is the proposition to develop advanced assistance systems for vulnerable road users (VRUs) such as bicyclists. We focus on the dooring problem, i.e., car doors being opened inattentively in the way of an approaching cyclist. We extended our vehicle to everything (V2X) communication-enabled virtual cycling environment for dooring experiments. Our system extends toolkits that are widely used in the V2X research community. We showcase how such a system may be used to realize and evaluate distributed algorithms for VRU safety solutions such as dooring prevention.

CCS CONCEPTS

• **Networks** → **Application layer protocols**; **Network simulations**; • **Human-centered computing** → *Empirical studies in HCI*.

KEYWORDS

Vehicular networking, intelligent transportation systems, vulnerable road users

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1 INTRODUCTION

We have seen many new advanced driver assistance systems (ADAS) appearing. Here, V2X communication-based safety solutions show great promise, and they are getting even more relevant in beyond-5G and now 6G networks [4]. So far, a lot of research focus lies on ADAS for motorized vehicles. However, research on developing assistance systems specifically for cyclists and pedestrians is still lagging behind. In the near future, it could become commonplace to find bicycles with integrated sensors and V2X capabilities, which would make the implementation of distributed ADAS for VRUs possible. As one of several other critical building blocks, such assistance systems for VRUs will hopefully get us closer to the goal of Vision Zero, i.e., zero people suffering severe injuries in traffic.

Figure 1: Painted bike lane overlapping with the door zone of parked cars.

In this paper, we concentrate on safety systems for bicyclists and how to evaluate these safely in empirical studies. One big problem standing out for bicyclists in particular is *dooring*, which happens when a car occupant opens a door at the same time as a cyclist is about to pass the vehicle with a short distance as demonstrated in Figure 1. Prevention techniques include behavioral advice for both car occupants and cyclists, infrastructure, as well as a limited number of upcoming assistance systems based on local sensor data. We give an overview of some of these techniques in Section 2.2.

The next step is to integrate V2X communication between cars and bicycles into warning features for both car passengers and cyclists, or temporary automatic door-blocking features. This idea has, for instance, been explored in the Safety4Bikes project [10]. In particular, it has been suggested to extend the IEEE 802.11p protocol and integrate VRUs into context awareness messages (CAMs) transmitted between vehicles. Before testing such safety-critical assistance systems on the road, it is helpful to conduct experiments in a safer virtualized environment, e.g., using the virtual cycling environment (VCE) [5].

We study the dooring problem in more depth and suggest V2X-based solutions. For this, we integrated a dooring scenario into the VCE for safe studies of V2X communication-based dooring solutions.

L. Stratmann and N.C. Banh contributed equally to the paper; L. Stratmnann on the networking side and N.C. Banh on the psychological side.

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Our main contributions can be summarized as follows:

- We highlight the dooring problem and the need to work on a bidirectional coordination between bicyclists and cars;
- we extended our V2X communication-enabled VCE for dooring studies; and
- we showcase how to realize and evaluate distributed algorithms for VRU safety solutions such as dooring prevention

2 THE DOORING PROBLEM

2.1 Problem Formulation

The dooring problem occurs when a car occupant opens a car door and when a cyclist, intending to pass the car closely, has no time to brake and no time or no space to evade said door, resulting in a crash. As an example, traffic violating behavior when entering or exiting a vehicle was the third most common recorded cause of bicycle accidents in Berlin in 2021 when the accident was caused by another road user.[1] Reducing the risk of dooring would therefore have a significant impact on bicycling safety.

Potential causes may be categorized by:

(a) A person opening the vehicle door is obliged to check for other road users.
(b) Cyclists are advised to keep at least 1 m distance from stopped vehicles. Not doing so may lead to the cyclist being partially blamed for the crash in Germany.[2]
(c) Observing this rule is often not possible when using the available and sometimes mandated cycling infrastructure.

If bike lanes are designated immediately adjacent to parking lots as shown in Figure 1, cyclists are forced to choose between risking a dooring accident, not using the bike lane, or only riding on the outer edge of the bike lane, and as a consequence subjecting themselves to illegal close passes [14].

2.2 Identification of Bicyclists and Crash Prevention Techniques

There are several ways to reduce the risk of dooring. A common recommendation is for car occupants to use the Dutch Reach,[3] i.e., to open the left door with the right hand and vice versa, so as to force oneself to turn to look over one's shoulder. Another way is to address the infrastructural issues above, for example by prohibiting road-side parking and by adequately separating bike lanes from door zones. Prosecuting illegal parking and too-close overtaking would allow cyclists to feel safer when keeping the recommended distance from parked vehicles.

Since changing road infrastructure and educating both drivers and cyclists will take time and political initiative, advanced assistance systems may offer valuable safety improvements in the interim. Most dooring-related ADAS efforts have so far primarily been made for cars. Car manufacturers have begun to implement warnings for approaching cars when people reach for the door, an early example being the exit warning systems of Audi or Mercedes.[4] Recently, Hyundai[5] and Ford[6] presented blocking doors partially or wholly as a dooring prevention measure. It has also been proposed to warn cyclists of opening doors using light signals on or near the car [15]. Bicyclists can be identified directly by RADAR, LiDAR, or ultrasound; as well as video-based solutions.

There are very few publications about technology-based bicycle-side accident mitigation systems. Mellinger and Weißmann [9] compiled an overview about the recent work in this field. Studies involving a pedelec were conducted both on testing grounds and in real traffic to evaluate haptic warnings from a V2X communication system. The bicyclist and the car driver were warned by different modalities based on their locations, which were transmitted from a smartphone to a centralized server. The authors note that the determination of position was erratic, which may be improved with local positioning systems. Oczko et al. [10] likewise report positive user feedback on V2X-based haptic warnings for cyclists.

2.3 V2X-Based Safety Systems for VRUs

V2X communication is going to be implemented in more and more cars in the coming years, among other purposes also for new ADAS such as preventing lane merging accidents through cooperative driving or to support platooning [8]. If this technology is going to be present in a large fraction of motorized vehicles, we may consider using a portion of the same exchanged messages also as VRUs, for example to make drivers more aware of our presence or to receive warnings of hazardous situations. This communication can be achieved by using CAM beaconing, for example.

While camera-based assistance systems for cyclists may already be implemented without the requirement of sufficient V2X market penetration, V2X communication has the potential to cover dangerous situations that are still out of view for the cyclist, thus giving road users more time to react [5]. In the dooring context, a camera's view may be obstructed by other parked vehicles, for example.

Even though V2X communication in the context of VRUs is still a growing area of research, some notable work has already been done. One important question, for instance, is which communication technology to use that would lend itself to mass adoption among both cyclists and drivers. Bluetooth Low Energy (BLE) is one promising option, which allows for connectionless communication via advertising beacons, is already available on most available smartphones, and which has been proposed for V2X communication in the past [1]. In the future, cellular device-to-device communication may become another viable option.

It has been proposed to use V2X communication to connect cyclists for the formation of bicycle platoons [3]. In this particular case, the authors use the IEEE 802.15.4 standard to coordinate a cooperative adaptive cruise control (CACC) system in both interactive and non-interactive simulations. Besides cyclists, cellular V2X communication has also been proposed for warning pedestrians for example of drivers exceeding the speed limit [7]. Such a system may remain useful even as intelligent speed assistance (ISA) systems

[1] Road traffic safety report for Berlin, 2021, https://www.berlin.de/polizei/_assets/aufgaben/anlagen-verkehrssicherheit/verkehrssicherheitslage_2021_in_berlin.pdf
[2] Court ruling OLG Jena, Az. 5 U 596/06, 2008
[3] https://www.dutchreach.org/dooring-problem-prevalence/
[4] https://www.audi-technology-portal.de/en/electrics-electronics/driver-assistant-systems/audi-a4-exit-warning-en, https://moba.i.mercedes-benz.com/baix/cars/177.0_mbux-high_2018_a/de_DE/page/ID_680f413b4fde9a2b354ae36578d07aff-3f9c030daa093869354ae36528c4d931-de-DE.html
[5] https://www.hyundai.news/eu/articles/stories/safe-exit-assist-how-does-it-work.html
[6] https://media.ford.com/content/fordmedia/feu/de/de/news/2020/02/27/ford-entwickelt-technologie--um-fahrrad--und-autofahrer-vor-door.html

recently became mandatory in new cars in the European Union, since these systems are explicitly not equivalent to speed limiters, such as those in electric scooters and bicycles, and allow drivers to override them.[7]

Accidents caused by truck drivers turning right at an intersections are a common risk of severe injury or death. In these situations, V2X communication may help by using regularly emitted beacon signals with the position, heading, and speed of each vehicle. Baqer and Krings [2] explore the possibility that such signals may temporarily be blocked, which they show can be mitigated by extrapolating future positions of both vehicles using *dead reckoning*.

With regards to safety systems that protect against dooring, V2X communication has already been a consideration, for example in [13]. The focus of said publication is on the effectiveness and usability of different dooring warning signals implemented in a smart bicycle helmet for a simulation environment, while assuming that the necessary V2X infrastructure is already present. According to the results, the most effective method is using a head-mounted display in combination with auditory cues to notice the danger as early as possible and to have time for performing evasive maneuvers.

3 TOWARDS EMPIRICAL STUDIES

It is important to assess the performance of ADAS in terms of improved safety, usability, and reliability. Especially for safety-critical systems, it is important to ensure that no participants will be harmed in these assessments. We now introduce a simulation-based approach with a human in the loop [5] for empirical studies.

These studies should not only assess dooring accidents but also those cognitive processes that are involved in cycling behavior or accidents. One such fundamental process is attention [11]. Attention is a very limited resource and has to be carefully divided among the many competing stimuli and tasks that people constantly encounter and solve: A lack of focused attention is among the important risks for accidents, viz., an important factor in safe driving [12]. This question is of high relevance for ADAS, and all the more so because all ADAS bind a certain amount of attention.

3.1 Virtual Cycling Environment

The virtual cycling environment (VCE) [5] is a simulation framework that allows for developing and analyzing V2X-based assistance systems for cyclists in an interactive human-in-the-loop environment. It connects SUMO[8] for the simulation of road traffic and Veins[9] for the simulation of any modern V2X communication protocol with a real-time component in the form of a bicycle on a training stand. Participants of an experiment can ride this bicycle and in this way interact with a representation of the simulation in Unity 3D that is shown to them either on a monitor cave or with VR glasses. We later extended the physical bicycle in the VCE with vibration motors in the handle bar for haptic signals to enable a comparison of subjective effectiveness of visual, acoustic, and haptic warnings [10].

[7]https://road-safety-charter.ec.europa.eu/resources-knowledge/media-and-press/intelligent-speed-assistance-isa-set-become-mandatory-across_en
[8]https://www.eclipse.org/sumo/
[9]http://veins.car2x.org/

Figure 2: In-game / in-simulation dooring scenario

The earlier VCE [6] was extended considerably to create a more realistic and more complex driving environment (see Figure 2). Parking lanes were added on the designated route of the cyclist and occupied by parked cars, which were semi-randomly spaced and angled. These cars are used for the dooring events. Additionally, different building types, vegetation, construction sites, and other everyday elements of streets were added. There was constant traffic on the lane next to the bicycle lane to prevent participants from sheering into the car lane. This would otherwise have allowed them to avoid dooring altogether.

3.2 Realizing and Evaluating Distributed Algorithms

For a successful dooring prevention ADAS, a multitude of stationary cars and mobile bicycles have to be able to communicate and cooperate. This requires an appropriate choice of hardware, communication technology, and software.

On the one hand, hardware needs to be able to be integrated both in cars and with bicycles. Especially in the latter case it is important for widespread adoption that such hardware is inexpensive, light-weight, low-power, or ideally already available in the smartphones that most people already own. On the other hand, the communication technology to be used for dooring warnings should be reliable, low-latency, and have sufficient reach to give cyclist and car occupant time to react.

We consider it an important question for further research where and on which device or devices computations will be made. While it might be possible to design light-weight protocols for dooring prevention that will already have a large impact on safety, there may come a point where machine learning would promise even larger safety gains at the cost of higher computation requirements. Cyclist trajectory prediction could be one such example. In such a case, we will have to decide whether to do (re)computations on an integrated bicycle computer, on a smartphone, in the cloud, or distributedly in the local environment. The first two options come with the drawback that cyclists would need to invest in sufficiently powerful hardware and that algorithms are more constrained by batter drain. Cloud computations may introduce delays that might be too high in safety-critical applications. Distributed local computing needs sufficient market penetration, but otherwise has the potential to avoid these drawbacks.

In order to find (a) a communication technology to reduce the risk of dooring and (b) one or more ADAS that work well with actual human beings, we may employ a set of simulation tools. For investigating (a) in isolation, a simulator like OMNeT++ is typically a good choice, and when used with Veins and SUMO it is also

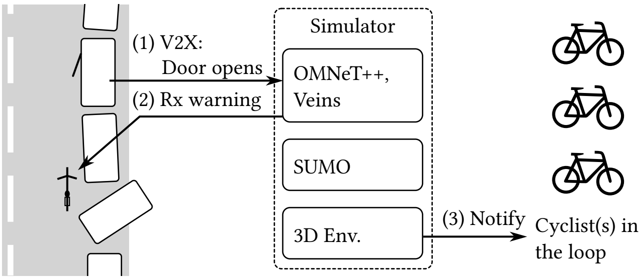

Figure 3: Architecture of the VCE for evaluating distributed ADAS for dooring warnings

possible to take road mobility into account. Combining these tools with the VCE opens up the possibility to experiment on (b) or even to investigate (a) and (b) in conjunction. The example shown in Figure 3 assumes the following steps: The first event (1) is the opening of any car door in the simulation. This event can be triggered based on a given probability and the position of the ego vehicle. When the application in a car notices that one of its doors is about to open, a beacon can be transmitted using V2X, which we simulate in OMNeT++ and Veins. Under ideal simulated circumstances, this warning is then received by the approaching bicycle in step (2), which is running its own independent Veins application. This received warning is then forwarded to the human in the loop in step (3). Here the warning may trigger a visual or audible alarm, haptic feedback, or any other conceivable safety mechanism like automatic emergency braking, for example. Similarly, a car occupant can be warned not to open their door if beacons of an approaching cyclist are being received.

A tool like the VCE offers further flexibility of the research questions that we can ask due to its modularity. Most components shown in Figure 3 are actually optional; for example, simulations may be run with or without car traffic (SUMO), with a single interactive user or with the multi-user interface, over the internet or locally, on a real bicycle on a training stand or simply with keyboard controls.

4 OPEN ISSUES AND CONCLUSION

Vulnerable road users (VRUs) are often not considered in modern ADAS-based safety solutions. We concentrate on bicyclists and one particular problem, which is widespread particularly in city environments, namely dooring. Dooring remains an open issue and, despite the efforts from the automotive industry to provide initial safety solutions, it is continuing to cause many accidents on the road. Existing solutions focus on sensor-based bike detection combined with audiovisual notifications to the driver or passenger, sometimes even with automated blocking mechanisms preventing the door from opening in a safety critical situation. Sensors like cameras, radar, and lidar all have two key issues: they require line of sight to the bicyclist and they work from the car's perspective only. V2X-based solutions would overcome some of these deficiencies. The technology is inherently bidirectional and can warn both the people in the car as well as the bicyclist.

We presented a general overview to the problem. Our main contribution, however, is on concepts and mechanisms to study the effectiveness of safety solutions for bicycles – using dooring as a prime example. The evaluation of such solutions is quite complex. Empirical studies are recommended from the psychology domain. Experimenting on the road using real bicycles, however, is too dangerous. We introduce an experimental setup based on simulation to overcome these limitations. We believe that our work particularly supports distributed V2X-based safety systems, since the simulation environment is well-suited for this purpose.

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REFERENCES

[1] Andrea Aza, David Melendi, Roberto García, Xabiel G. Pañeda, Laura Pozueco, and Víctor Corcoba. 2022. Bluetooth 5 performance analysis for inter-vehicular communications. *Wireless Networks* 28, 1 (Nov. 2022), 137–159. https://doi.org/10.1007/s11276-021-02830-9

[2] Mohammad Baqer and Axel W. Krings. 2019. Reliability of VANET Bicycle Safety Applications in Malicious Environments. In *Telecommunications TELFOR*. IEEE, Belgrade, Serbia. https://doi.org/10.1109/telfor48224.2019.8971200

[3] Sandra Céspedes, Juan Salamanca, Alexis Yáñez, and Daniel Vinasco. 2019. Group Cycling Meets Technology: A Cooperative Cycling Cyber-Physical System. *IEEE Transactions on Intelligent Transportation Systems* 20, 8 (Aug. 2019), 3178–3188. https://doi.org/10.1109/tits.2018.2874394

[4] Falko Dressler, Florian Klingler, Michele Segata, and Renato Lo Cigno. 2019. Cooperative Driving and the Tactile Internet. *Proc. IEEE* 107, 2 (Feb. 2019), 436–446. https://doi.org/10.1109/JPROC.2018.2863026

[5] Julian Heinovski, Lukas Stratmann, Dominik S. Buse, Florian Klingler, Mario Franke, Marie-Christin H. Oczko, Christoph Sommer, Ingrid Scharlau, and Falko Dressler. 2019. Modeling Cycling Behavior to Improve Bicyclists' Safety at Intersections – A Networking Perspective. In *IEEE WoWMoM 2019*. IEEE, Washington, D.C. https://doi.org/10.1109/WoWMoM.2019.8793008

[6] Alexander Krüger, Jan Tünnermann, Lukas Stratmann, Lucas Briese, Falko Dressler, and Ingrid Scharlau. 2021. TVA in the wild: Applying the theory of visual attention to game-like and less controlled experiments. *Open Psychology* 3, 1 (April 2021), 1–46. https://doi.org/10.1515/psych-2021-0001

[7] Chi-Yu Li, Giovanni Salinas, Po-Hao Huang, Guan-Hua Tu, Guo-Huang Hsu, and Tien-Yuan Hsieh. 2018. V2PSense: Enabling Cellular-Based V2P Collision Warning Service Through Mobile Sensing. In *IEEE ICC 2018*. IEEE, Kansas City, MO. https://doi.org/10.1109/icc.2018.8422981

[8] Barbara M Masini, Alberto Zanella, Gianni Pasolini, Alessandro Bazzi, Flavio Zabini, Oreste Andrisano, Mirko Mirabella, and Paolo Toppan. 2020. Toward the Integration of ADAS Capabilities in V2X Communications for Cooperative Driving. In *International AEIT AUTOMOTIVE*. IEEE, Turin, Italy. https://doi.org/10.23919/aeitautomotive50086.2020.9307433

[9] Nicolas Mellinger and Andreas Weißmann. 2021. Fahrzeugtechnische Maßnahmen zur Erhöhung der Radverkehrssicherheit - das MARS Forschungsprojekt. In *Symposium Unfallforschung 2021*, Vol. 8. Cuvillier Verlag, 89–106.

[10] Marie-Christin H. Oczko, Lukas Stratmann, Mario Franke, Julian Heinovski, Dominik S. Buse, Florian Klingler, and Falko Dressler. 2020. Integrating Haptic Signals with V2X-based Safety Systems for Vulnerable Road Users. In *IEEE ICNC 2020*. IEEE, Big Island, HI. https://doi.org/10.1109/ICNC47757.2020.9049723

[11] Michael I Posner and Yoav Cohen. 1984. Components of visual orienting. *Attention and performance X: Control of language processes* 32 (1984), 531–556.

[12] David L. Strayer and Frank A. Drews. 2006. Multitasking in the Automobile. In *Attention: From Theory to Practice*, Arthur F. Kramer, Douglas A. Wiegmann, and Alex Kirlik (Eds.). OUP, Oxford, United Kingdom, 121–133. https://doi.org/10.1093/acprof:oso/9780195305722.003.0009

[13] Tamara von Sawitzky, Thomas Grauschopf, and Andreas Riener. 2021. "Attention! A Door Could Open." - Introducing Awareness Messages for Cyclists to Safely Evade Potential Hazards. *Multimodal Technologies and Interaction* 6, 1 (Dec. 2021). https://doi.org/10.3390/mti6010003

[14] Rul von Stülpnagel, Rafael Hologa, and Nils Riach. 2022. Cars overtaking cyclists on different urban road types – Expectations about passing safety are not aligned with observed passing distances. *Transportation Research Part F: Traffic Psychology and Behaviour* 89 (Aug. 2022), 334–346. https://doi.org/10.1016/j.trf.2022.07.005

[15] Bo Yang, Jieqing Ning, Tsutomu Kaizuka, Munetaka Nishihira, and Kimihiko Nakano. 2022. Effects of Exterior Lighting System of Parked Vehicles on the Behaviors of Cyclists. *IEEE Transactions on Intelligent Transportation Systems* 23, 8 (Aug. 2022), 12451–12463. https://doi.org/10.1109/tits.2021.3114431