

Modeling Cycling Behavior to Improve Bicyclists' Safety at Intersections – A Networking Perspective

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Abstract—Road traffic is continuously increasing worldwide and Vulnerable Road Users (VRUs) such as bicyclists are ever more susceptible to injuries from crashes. Vehicular Ad-hoc Network (VANET) technologies in combination with Advanced Driver Assistance Systems (ADAS) are currently being evaluated to enhance road traffic safety. The same technology is now also considered for warning cyclists about imminent crashes. Prototypes for such VANET-enabled bicycles already exist, however, the primary problem here is verification and test due to immediate safety concerns for the participants. Computer simulation is considered a more feasible alternative; however, realistic behavior models of VRUs are not available in the required quality and quantity. We developed a virtual cycling environment to address this issue, allowing to study and record cyclists' behavior. We collected (and make available) traces from a variety of subjects cycling towards an intersection for three different safety critical scenarios. As proof of concept, we then used these traces in our vehicular networking simulation framework to assess the impact of a simple VANET solution on the cyclists' safety. Our results demonstrate the need for such an integrated framework for empirical studies as well as for simulation-based exploration of system configurations.

I. INTRODUCTION

Improving road traffic safety has been a cornerstone of modern research and development in vehicular networking [1] – and great leaps have been made in the past years to reduce both injuries and fatalities of road users. In the past, however, much of the effort has focused on cars and motorway traffic. Yet, as a recent report [2] by the European Union also highlights, only a small fraction (here, about 8%) of road fatalities occur on motorways; the vast majority happen on rural and urban roads, which are characterized by intersections. Moreover, car occupants only account for roughly half of the victims, the other half being Vulnerable Road Users (VRUs) such as bicyclists – with both children and the elderly being particularly at risk. Even though motorcycle crashes have been investigated in much detail already, this does not hold for bicyclists.

In both cases, the most common type of crash is related to another road user pulling out of a junction and into the path of (but failing to recognize) a cyclist. This is commonly termed the *look but fail to see* error [3]: The drivers are reported to have been careful and attentive but still failed

to see an oncoming road user. Most of such crashes happen at uncontrolled intersections in urban environments [4].

We therefore look towards opportunities to improve bicyclists' safety at intersections, but find that literature studying this field commonly abstracts away from either realistic bicycle mobility (i.e., kinematics and behavior) or wireless networking effects. There is obviously the need for modeling cycling behavior to better study both the bicyclist's visual search [5] and the effects of technical assistance systems such as Advanced Driver Assistance Systems (ADAS) using vehicular networking.

In this paper, we fill this gap by detailing a methodology to record real bicycle mobility traces in a safe and controlled fashion, i.e., without putting participants at risk. We do this by employing Virtual Reality (VR) technology to let participants ride a real bicycle through a simulated 3D scenario featuring intersecting roads and cycleways with or without signage and/or blocking their Line-of-Sight (LOS). We can then reproduce cyclists' movements by replaying these traces in a computer simulation using the popular Veins vehicular networking simulator [6], e.g., to investigate the impact of wireless warning systems on road user safety.

As a proof of concept, we include the results of a small simulation study of three different scenarios where bicycles and cars cross paths at an intersection, investigating the potential benefit of a simple wireless warning system that notifies either bicycles or cars of potential danger.

Our main contributions can be summarized as follows:

- We present a methodology for recording real bicyclists' behavior in simulated, potentially "dangerous" road traffic scenarios;
- we make such recorded data available¹ to the research community, so that it may serve as the basis for own experiments using realistic bicycle movement;
- we demonstrate how this data can be used in computer simulations using highly detailed wireless networking models to investigate the efficiency of potential wireless warning systems; and
- we include a proof of concept study of a wireless warning system which highlights the impact of both wireless networking effects and bicyclists' behavior on results.

II. RELATED WORK

Several systems for reducing the number of car-to-bicycle collisions have been investigated in the past. This includes, for example, auditory, visual, and haptic feedback for children [7], as well as warning systems based on Vehicle-to-Vehicle (V2V) communication [8], [9] or on image processing from a rear-facing camera [10].

One way to ensure that the verification process is as realistic as possible is to conduct field tests. For example, Anaya et al. [8] followed this approach and performed an empirical study of a novel ADAS focusing on avoiding accidents that involve motorcyclists and cyclists using V2V communications. However, this approach is limited in the number of trial runs that can be completed in a reasonable amount of time. Additionally, the set of possible scenarios is constrained by the amount of risk test persons can be subjected to.

First efforts have been made to develop realistic mobility models for bicyclists [11]–[14]. However, according to Ma and Luo [14], “*bicycle traffic is still far from well understood.*” This is evidenced by the fact that, to the best of our knowledge, and with the exception of work by Guo et al. [12], research so far has been focused mostly on the longitudinal component of bicyclists’ motion. Guo et al. [12] investigate cyclists’ lane keeping behavior in the particular situation when they leave the cycling lane and cross into the motor lane. So far, however, realistic models for cyclist mobility at intersections seem to be missing.

Thus, following a different methodology, Kim et al. [9] verified their results in computer simulation using the commercial software packages PreScan and MATLAB, eliminating the need for participants and thus the concern for their safety. Although they mention the possibility of using third party vehicle dynamics models, no details are given on which specific model they used for their simulated bicycle, leaving the cycling behavior being rather abstract.

An alternative approach was used by Matviienko et al. [7]. They had underage participants sit on a stationary bicycle equipped with sensors and instructed them to ride through a virtual environment based on a commercial car driving simulator called SILAB. The focus of their work, though, was on the aspect of human-machine interaction rather than wireless communication.

We aim to fill this gap by presenting a tool that can record realistic traces of different participants for arbitrary scenarios, which can later be used in highly realistic computer simulations that support both the vehicular networking aspect as well as other road traffic, i.e., cars.

III. SAFETY FOR BIKES

In the project Safety4Bikes,² we look into ways for increasing the road traffic safety for cyclists by developing novel ADAS and, most importantly, integrating these with vehicular networking. We particularly developed a prototype, nick-named the *Silver Box*, which provides standard compliant

²<https://www.safety4bikes.de>

communication between the bicycle and cars. In this paper, however, we emphasize on a novel Virtual Cycling Environment (VCE), which allows for empirical studies in a safe and well-controlled environment as well as to collect traces, which we can later re-use in computer simulation. In the following, we outline the core ideas and components of both systems.

A. Wireless Communication: The Silver Box

A fundamental building block in the Safety4Bikes architecture is the wireless communication between motorized vehicles and VRUs in order to inform vehicles about potential cyclists within their vicinity. Research on wireless communication in the context of vehicular networks evolved from pure theoretical studies more than a decade ago to standardized communication protocols supported by prototypes and field tests [15], [16]. These standards include ETSI ITS-G5 [17] in Europe and IEEE 1609.4 DSRC/WAVE [18] in the U.S., both building upon IEEE 802.11p WLAN [19]. All these standards have been developed for motorized vehicles and only little attention was paid to VRUs such as cyclists [20].

The core of the ETSI ITS-G5 standard is the Cooperative Awareness Message (CAM) [21], which is periodically broadcast by each vehicle. CAMs are used to enhance the awareness among all vehicles in communication range, and eventually to support cooperative driving maneuvers. It provides basic information of the originating vehicle like vehicle type, position, and speed. Vehicles receiving a CAM can analyze the information and, thus, become able to evaluate the risk of a probable collision. To support transmission of event-based information, ETSI-ITS G5 defines an additional message type, namely Decentralized Environmental Notification Messages (DENMs) [22]. These messages are used to inform neighboring vehicles about events the originating vehicle has detected, e.g., dangerous traffic situations, adverse weather conditions, hazardous locations.

In earlier work [20], we outlined important shortcomings of the current CAM related to VRUs. For example, it is difficult to incorporate important information specific to cyclists. Consequently, we presented an extension to the current CAM specification to allow integrating cyclist-related information elements (e.g., a new *CyclistSubType* data field) while maintaining backwards compatibility with the standard.

The next step was to integrate support for these protocols for bicycles in the form of an ADAS. For the development of the Silver Box, which supports all our extensions, we have built upon our OpenC2X platform [15], which represents an ETSI ITS-G5 compliant Open Source implementation of the networking stack using commodity hardware. We extend the system to support transmitting and receiving VRU related information within CAMs. This way it is possible to deploy our system to embedded devices, which can easily be integrated, for example, with e-bikes.

B. Virtual Cycling Environment

In order to trace and record realistic and reliable cyclist behavior, we developed the Virtual Cycling Environment (VCE), which we now made available as Open Source.¹

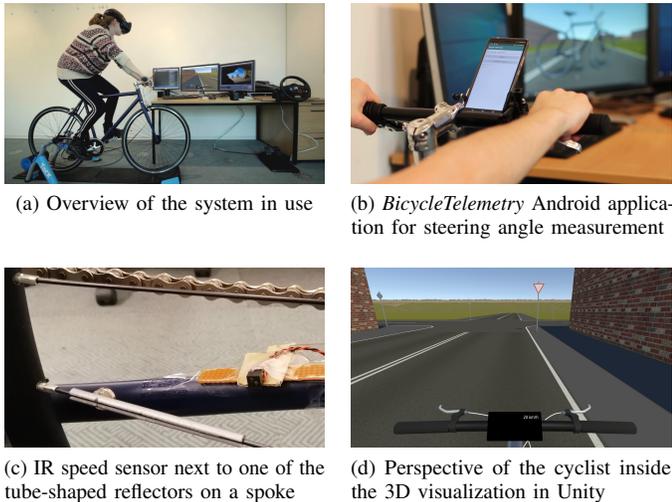


Figure 1. Virtual Cycling Environment (VCE)

It allows cyclists to ride a virtual bicycle in a 3D virtual reality environment by interacting with a physical bicycle on a training stand, as shown in Figure 1. Foreign traffic (i.e., cars) and wireless networking are provided by the specialized simulators SUMO [23] and Veins [6], respectively. The physical bike simulator is then coupled via the Ego-Vehicle Interface (EVI) [24] to this simulation platform. The VCE provides a high degree of realism to the cyclist, thanks to the haptics of a physical bicycle combined with virtual reality systems. Researchers can leverage this to study the interaction of cyclists and their traffic environment without the danger of physical harm. Thanks to the coupling to Veins, even future assistance systems relying on communication can be tested.

Conceptually, the VCE is composed of three parts (see Figure 2): (1) A user interface, consisting of a physical bicycle with sensors as an input device and a VR headset as an output device; (2) a 3D simulation environment, consisting of the kinematics model of the bicycle and the 3D visualization of the environment; and (3) a V2X simulator (Veins), consisting of the traffic simulator SUMO, the network simulator running in OMNeT++, and the EVI to provide real-time coupling. All components are connected via an IP network, allowing them to exchange messages (typically UDP). In the following, the individual components are described in detail.

The core of the user input device of the VCE is a standard

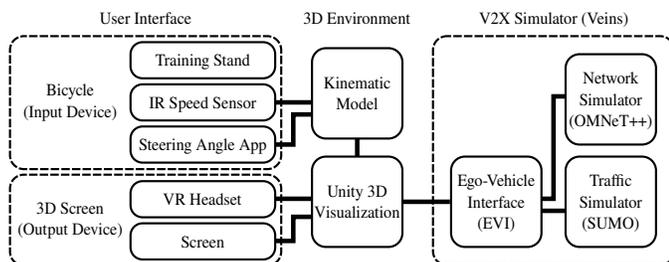


Figure 2. Virtual Cycling Environment (VCE) components

bicycle placed on a training stand (as shown in Figure 1a). Cyclists can steer and pedal on the stand without actually moving the bicycle. Visual feedback is provided via a VR Headset or a monitor placed in front of the bicycle. An eddy current brake attached to the back wheel provides cycling resistance as well as inertia to the bicycle. The resistance of the eddy current brake can be adapted with a dial, e.g., to simulate inclination or different gears. Cycling behavior is measured using a speed sensor on the back wheel and a steering angle sensor on the handlebar. For a smooth experience, we require an update rate of at least 10 Hz for all sensors and the kinematics model. While the bicycle stand already came with some sensors, they did not fulfill our requirements in terms of open protocols, reliability, sampling rate, and precision. We thus added our own custom sensors.

The steering angle is measured by a smartphone mounted on the handlebar, running our android app *BicycleTelemetry* (see Figure 1b). The app uses the smartphone’s magnetometer and accelerometer and can be calibrated to define the straight-ahead orientation of the handlebar. To compensate for some of the noise registered by the smartphone sensors, especially when a cyclist is actively pedaling, we employed a dead zone of 7° . Resulting steering angles are pushed to the kinematics model via UDP at a target rate of 20 Hz.

The speed is measured by a custom sensor built with an IR detector and nine tube-shaped reflectors mounted on the back wheel (see Figure 1c). An embedded Linux PC (i.e., a Raspberry Pi) detects whenever a reflector passes the sensor. By measuring the time interval between two detections, the speed of the wheel is derived. The nine reflectors yield a resolution of 40° , or about 0.15 m for our bicycle. Thus, the speed sensor does not have a fixed sampling frequency, but even at very low cycling speeds, the requirement of 10 Hz is easily met. A dynamic timeout (i.e., the combined duration of the last three detections) is used to detect abruptly engaged brakes.

The kinematics model combines all sensor inputs to compute the current state of the virtual bicycle for the VCE. It outputs the current position (in Cartesian coordinates), heading (of the bicycle frame as well as of the steering handle), and speed. The model produces new outputs and sends updates to the 3D visualization software, again at a target rate of 10 Hz. These updates can also be written to a file to record a trace (e.g., for the use in large-scale simulations, see Section IV-C).

We employ Unity to create a 3D visualization of the bicycle (see Figure 1d) and its environment. The virtual bicycle’s position is obtained from the kinematics model. Using the SteamVR integration, the render camera of the visualization can automatically track the orientation of the cyclist wearing the VR headset (an HTC Vive). The scene around the virtual bicycle is automatically generated at start time from a SUMO scenario. Currently, this includes roads, cycling lanes, footpaths, as well as traffic lights, basic building shapes, and a number of street signs (implemented as custom points of interest in SUMO). As SUMO scenarios can be created from OpenStreetMap data, it is easy to visualize scenarios based on real-world road networks.

The 3D visualization also acts as a client to the EVI, as

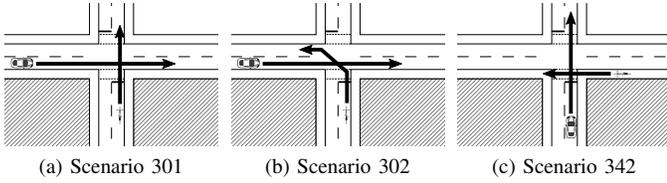


Figure 3. Considered traffic scenarios with high number of accidents involving motorized vehicles and children: A motorized vehicle and a bicycle are approaching the intersection from different directions.

was shown in earlier works for a car driving simulator [25]. This way, the virtual bicycle can be synchronized with Veins in real-time, which in turn provides ambient traffic (then rendered into the environment of the virtual bicycle) and network communication simulation.

IV. EXPERIMENTAL STUDY

In order to investigate the benefits of networked assistance systems for road traffic safety in the context of VRUs, we use our novel VCE framework to record realistic bicycle traces. We employed multiple bicyclists to model a variety of different cycling behavior. These traces will help to generate reproducible and large scale simulation studies for vehicular road traffic simulation. Before recording the traces, we carefully identified important (and thus dangerous) traffic situations for bicyclists in combination with motorized vehicles. We then modeled scenarios for our VCE platform for each of these traffic situations, allowing us to record bicycle traces representing realistic and detailed cycling behavior. These traces then serve as input for our coupled road traffic and network simulation, based on the popular Veins [6] simulator, investigating the benefits of wireless communication for road traffic safety.

A. Considered Scenarios

In order to achieve realistic and useful results in our approach for improving bicyclists safety at intersections, we consider important (i.e., safety critical) traffic scenarios in this study. Poschadel [26] describes and formalizes typical traffic scenarios that have a high number of accidents involving motorized vehicles and children (walking as well as on a bicycle). A subset of these scenarios involves intersections, which this study focuses on. We therefore selected the following intersection scenarios, which are especially dangerous.

1) *Scenario 301*: The scenario with the highest occurrence among all accidents caused by children is 301 [26, Figure 47], which is shown in Figure 3a. This scenario has the third highest occurrence among all accidents involving motorized vehicles and children [26, Table 11]. In this scenario, a cyclist arrives at the intersection from the road in the south and has to yield the right of way to other vehicles coming from east or west. After crossing the intersection, the cyclist wants to continue straight to the north. A motorized vehicle, such as a car, is arriving at the intersection from the road in the west. It has the right of way and wants to continue to the east after crossing the intersection. Typically, an accident occurs in this scenario because the cyclist is not yielding the right of way to

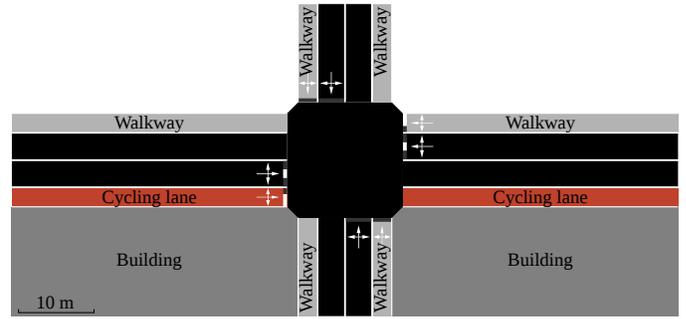


Figure 4. Zoomed-in screenshot of modeled road network. An intersection with four roads of equal length & width, corresponding sidewalks (grey color), & cycling lanes (red). Two buildings in the south block direct LOS between corresponding roads.

the car, and, instead, crosses the intersection without waiting. The scenario becomes more complex considering buildings blocking the direct LOS between driver and cyclist.

2) *Scenario 302*: A similar situation is described by scenario 302, which is shown in Figure 3b. This scenario leads to the highest number of accidents caused by children for taking a turn at intersections [26, Table 11]. Here, the cyclist again arrives at the intersection from the road in the south. However, this time, the cyclist turns left at the intersection and continues on the road in the west. A motorized vehicle again is arriving at the intersection from the road in the west and continues straight on the road in the east after crossing the intersection. In this scenario, an accident is most likely caused by the cyclist not yielding the right of way to the car. In addition, the building is blocking the LOS between the car and the cyclist.

3) *Scenario 342*: The scenario 342 has the highest occurrence among all accidents involving motorized vehicles and children [26, Table 11]. In this scenario, shown in Figure 3c, the cyclist arrives at the intersection from the road in the east, while cycling on its left sidewalk (i.e., on the wrong side). After crossing the intersection, the cyclist wants to continue straight on the road in the west. Now, the motorized vehicle is arriving at the intersection from the road in the south. It wants to continue straight as well, i.e., to the north, after crossing the intersection. In this situation, the car has to wait at the intersection, and the driver needs to watch out for crossing pedestrians. As the cyclist is riding on the wrong sidewalk and the LOS again is blocked by the building, the driver of the car might not spot the cyclist in time, thus an accident can easily occur.

B. Modeled Road Network

In order to apply the identified scenarios to our experimental study, we built a SUMO road network (see Figure 4). It consists of a central intersection of 4 orthogonal road legs, each with a single lane per direction. Each road has a length of 100 m from its starting point to the middle of the intersection and a width of 7 m. Consequently, each lane has a width of 3.5 m. Next to each lane, there is either a cycleway (south of the east-west road) or a walkway with a width of 2.5 m. Road users going from east to west or vice versa have the right of way at the

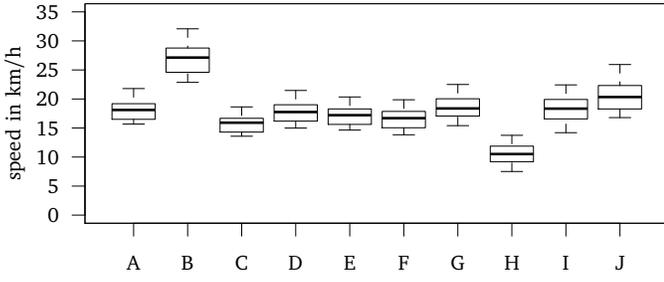


Figure 5. Cycling speed among trace repetitions separated by cyclist for scenario 342. The whiskers show the 5th and 95th percentile, respectively.

intersection. The south-west and south-east corners each are covered by a building, located directly next to the walkway or cycleway and stretching to the border of the scenario. These buildings block all LOS between road users on intersecting roads until they are close to the intersection. We converted this road network into a 3D scene for our visualization software Unity. There, the right of way is indicated by corresponding traffic signs, as shown in Figure 1d from the perspective of a cyclist starting in the south.

C. Recorded Bicycle Traces

We recruited 10 cyclists, 3 of them female, 7 male, aged 21 to 61 years, and recorded traces as input for the simulation study. Each cyclist repeated each of the 3 scenarios 3 times for a total of 9 traces per cyclist. At the beginning of every new scenario, cyclists were instructed on which route to take, whether the scenario required them to ride on the sidewalk or on the road, and they were told to cross the intersection without stopping. Cyclists were otherwise encouraged to ride at their natural pace. All traces were recorded using the VCE setup shown in Figure 1, including the VR headset. We let cyclists start each scenario with an offset of 20m from the beginning of the road in order to skip the acceleration phase. Trace recording was stopped for each run once the cyclist had passed the end of the respective scenario’s exit road. The traces are published on our VCE project page¹ as well.

In Figure 5, we plot the median together with the 5th and 95th percentile of the cycling speed for different cyclists in scenario 342. As can be seen, cyclists exhibit mostly similar behavior with differences in their cycling behavior still being discernible. This holds true for the cycling speed in scenario 342, but also, for example, for the steering behavior of individual cyclists.

D. Collision Detection

For studying safety improvements for cyclists in road traffic at intersection scenarios, an important aspect is to identify possible accidents. In order to detect such accidents in our simulation, we take advantage of a collision detector between road users (in our case, between a car and a bicycle). Since the SUMO simulator does not provide applicable collision detection mechanisms, we integrated our own implementation, which is based on the separating axis theorem [27]. This theorem allows to algorithmically decide whether two polygons are overlapping. By modeling each vehicle as a polygon, constructed from its

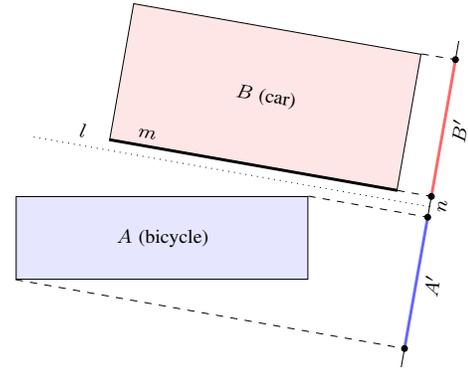


Figure 6. Separating axis theorem for convex shapes. One of many possible projections A' and B' of vehicles’ bounding boxes A and B onto a line n (for efficiency: a normal of one of their faces m) do not overlap. This implies that a line l was found that separates A and B : they do not overlap.

width and length, it is possible to detect colliding vehicles by using Algorithm 1.

Figure 6 shows an example of two polygons and how the theorem is used to compute a possible overlap. Using one possible normal to one side of the first polygon, all vertices of both polygons are orthogonally projected onto it. The projections of each polygon form a corresponding interval on the normal. These intervals do not overlap, thus, the corresponding polygons also do not overlap, hence, the vehicles did not collide. In case of an overlap, the next possible normal and the corresponding projections have to be checked until either a projection does not overlap or all possible normals are processed (cf. Algorithm 1).

Besides detecting actual collisions, the algorithm could also be used to warn of possible collisions: Instead of computing the rectangle based on the width and length of a vehicle, an additional buffer value could be added to create a warning zone around the vehicle.

E. Simulation Setup

To evaluate the benefits of communication between vehicles, in particular motorized vehicles and VRUs, such as bicyclists, we perform simulation studies for the discussed intersection

Algorithm 1 Collision detection using separating axis theorem

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Input: position of vehicles  $a$  and  $b$ , dimensions, and yaw
if distance of  $a$  and  $b$  is above threshold then
  return no collision (and terminate)  $\triangleright$  early exit
end if
compute bounding boxes  $A$  and  $B$  of vehicles  $a$  and  $b$ 
compute normals  $N$  to each face of both  $A$  and  $B$ 
for all normals  $n$  in  $N$  do
  project  $A$  and  $B$  onto  $n$ 
  if projections are not overlapping then
    return no collision (and terminate)  $\triangleright$  early exit
  end if
end for
return collision

```

scenarios (cf. Sections IV-A and IV-B). We configured the road traffic simulator SUMO to model the motorized traffic (i.e., a single car) [30] to keep a target driving speed. Bicycles are modeled in the Veins simulation only, using the recorded bicycle traces. By modifying the speed and the departure time of the motorized vehicle (see Table I), it is possible to provoke collisions with the bicycle, which we detect with our collision detection algorithm outlined in Section IV-D.

On the networking side, we configure each vehicle (i.e., the car and the bicycle) to execute a simple beaconing protocol. Each vehicle periodically transmits a small 1-hop broadcast message similar to the ETSI ITS-G5 CAM specification. Upon reception of such messages, vehicles become aware of the transmitting vehicle, even if there is no direct LOS between these two. This awareness helps to avoid dangerous situations at intersections where buildings are obstructing the LOS, but wireless communication through them is still possible. For simplicity, we consider a static beaconing approach with different beaconing frequencies, as outlined in Table I.

Radio communication is modeled using IEEE 802.11p to transmit at 5.890 GHz, whereas its attenuation is modeled by Friis path-loss and the building obstacle shadowing model by Sommer et al. [28] (cf. Table I). Further, we configured asymmetric transmit powers for the car and the bicycle, to represent the limited electrical energy and spatial capabilities of the bicycle in comparison to a motorized vehicle.

For statistical confidence, we repeat each configuration (i.e., a combination of scenario, cyclist, trace repetition, car's driving speed, car's departure time, and beaconing rate) 10 times.

Table I
SIMULATION PARAMETERS

Parameter	Value
Road traffic simulator (for cars)	SUMO 1.1.0
Wireless network simulator	Veins 5a1
Technology	IEEE 802.11p
Frame length	1680 bit
Modulation and coding scheme	QPSK R=1/2: 6 Mbit/s
Frequency and bandwidth	5.890 GHz, 10 MHz
Access category	AC_BK (user priority 1)
Transmit power of car	100 mW
Transmit power of bicycle	20 mW
Path loss (Friis model)	$\alpha = 2$
Shadowing (Building loss [28])	$\beta = 9$ dB, $\gamma = 0.4$ dB/m
Noise floor	-98 dBm
Antenna (monopole with ground plane)	[29]
Simulation time	60 s
Repetitions	10
Bicycle start time	0 s
Bicycle length	1.6 m
Bicycle width	0.65 m
Car movement model	Krauss [30] (SUMO 1.1.0)
Car length	4.3 m
Car width	1.8 m
Car speed	20–60 km/h, step 10 km/h
Car start time	0–41 s, step 0.1 s
Beaconing rate	1 Hz, 10 Hz, 40 Hz

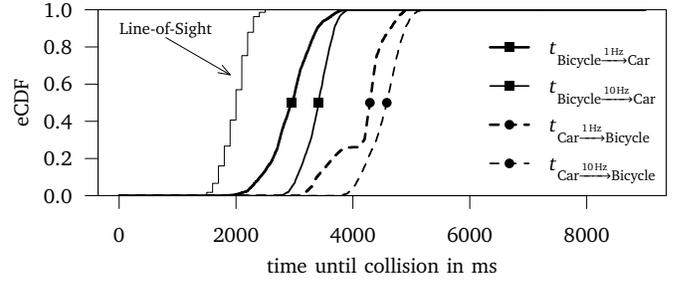


Figure 7. Time to collision in scenario 301 with the car driving at 30 km/h

F. Evaluation

To quantify the impact of wireless communication on safety for VRUs in road traffic situations at intersections, we measure the following timings in all those simulation runs which actually produce a collision between the car and the bicycle:

- 1) $t_{\text{Line-of-Sight}}$ corresponds to the time interval between the car and the bicycle being in LOS of each other and their collision. LOS here means that the driver of the car and the cyclist are theoretically able to see each other. Thus, this time interval shows the best-case time for both of them to take appropriate measures to avoid a collision without any Vehicular Ad-hoc Network (VANET) warning system in place.
- 2) $t_{\text{Bicycle}^{\text{TX}} \rightarrow \text{Car}}$ denotes the amount of time starting when the car is informed by the bicycle about its presence and ending at the time of collision. Thus, this value represents the time available to the car (or its driver) in order to avoid the collision with the bicycle by taking corresponding actions, such as stopping or slowing down.
- 3) $t_{\text{Car}^{\text{TX}} \rightarrow \text{Bicycle}}$ denotes the amount of time starting when the bicycle is informed by the car about its presence and ending at the time of collision. Analogously to before, the cyclist can take corresponding actions like slowing down or stopping. Since we configured a lower transmission power for the bicycle, we expect that this timing is slightly lower than $t_{\text{Bicycle}^{\text{TX}} \rightarrow \text{Car}}$.

Based on these metrics, we are able to quantify the impact of wireless communication on safety by evaluating the time of awareness in comparison to relying only on LOS. Since wireless communication can penetrate buildings, we expect it to gain additional warning time and, thus, be beneficial for the safety of the driver as well as the cyclist.

In a first experiment, we consider scenario 301 as explained in Section IV-A1. To recap: this scenario consists of an intersection where the car crosses the intersection from west and to east, while the bicycle crosses the street from south to north. Since the building obstructs the view at the intersection, the car and the bicycle are in LOS of each other only at a late point in time. Here, wireless communication could be beneficial by increasing the awareness time between the vehicles.

In Figure 7, we show results for a driving speed of 30 km/h for the car and two different beaconing rates, namely 1 Hz and 10 Hz. As can be seen, LOS between the car and the bicycle

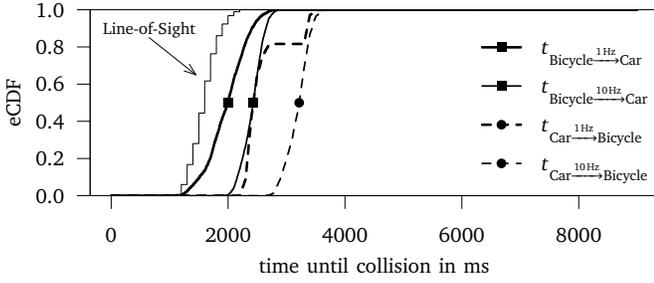


Figure 8. Time to collision in scenario 301 with the car driving at 50 km/h

is established at 2000 ms (median) before the collision. Due to discrete position updates for the simulated car, the distribution of this time consists of discrete values as well, which are multiples of the update interval. If we use 1 Hz beaoning, the awareness time increases to 2942 ms and 4291 ms for the car and the bicycle, respectively. This is due to the lower configured transmit power for the bicycle compared to the car. Thus, the bicycle is aware of the car earlier. Since modern cars are equipped with sensors and control systems able to perform safety measures such as emergency braking, a lower reaction time could be sufficient. Whereas for a bicycle, the awareness time has to be higher, because the cycling human has needs both reaction time and time for performing a collision avoiding maneuver.

When changing the beaoning frequency to 10 Hz, we see an increase in the warning time by 470 ms and 289 ms (median) for the car and the bicycle, respectively. This increase is related to the worst-case time between two beacon transmissions, which is reduced from 1000 ms to 100 ms, thus giving both vehicles a higher chance to be informed earlier. Naturally, when using extremely low beaoning frequencies (e.g., in the order of several seconds), it can happen that the warning message is received after the vehicles are in LOS of each other. On the other hand, for higher beaoning frequencies (e.g., 40 Hz, data not shown), only marginal improvements for the awareness time can be achieved. Therefore, we do not further discuss results for 40 Hz beaoning in the remainder of this paper.

Having a more detailed look at the distribution of warning times, we observe that both the beaoning frequency and the mobility of the vehicles have a great impact on the results. The travelled distance of the vehicles stays the same and is defined by the position when they are able to receive each other's beacons and are in LOS of each other. Thus, the time it takes to travel this distance heavily depends on the speed of the vehicle. This especially holds for the recorded bicycle traces described in Section IV-C, which show a variance in driving among different cyclists and also between multiple repetitions for individual cyclists.

We further investigate higher driving speeds of the car, in particular 50 km/h, and show the results in Figure 8. Naturally, we observe a lower median time interval (e.g., 1600 ms in comparison to 2000 ms) between the two road traffic participants being in LOS of each other and the collision, caused by the higher speed of the vehicles. Moreover, we

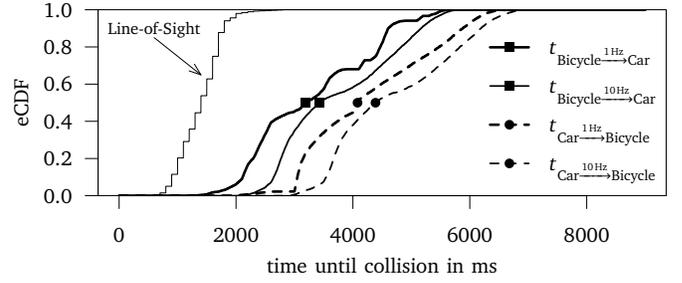


Figure 9. Time to collision in scenario 342 with the car driving at 40 km/h

observe that even a lower transmit power (cf. bicycle) and high beaoning frequency (e.g., 10 Hz) lead to qualitatively similar results compared to a high transmit power (cf. car) and a low beaoning frequency (e.g., 1 Hz) for a non-negligible number of road traffic participants. However, usually a higher transmit power also leads to longer warning times (e.g., 831 ms in comparison to 397 ms for the bicycle and the car, respectively).

When looking at simulation results for scenario 302, we observe qualitatively similar results for LOS and warning times in comparison to scenario 301. This is due to the similarity of both scenarios. Therefore, we omit further discussion of scenario 302.

On the other hand, scenario 342 is quite different to the previous ones. Therefore, in the following, we focus on results from this scenario. To recap: in scenario 342, the car crosses the intersection from south to north, while the bicycle moves from east to west on its cycling lane close to the building. The bicycle is located directly next to building until it is within close proximity of the intersection, thus leading to a late point in time where LOS to the car is possible. Hence, we expect $t_{\text{Line-of-Sight}}$ to decrease for this scenario.

Indeed, the results shown in Figure 9 confirm our expectations, as the median time is only 1400 ms. For a driving speed of 40 km/h, the median warning times for the two investigated beaoning frequencies (i.e., 1 Hz and 10 Hz) differ by 247 ms and 307 ms for the car and the bicycle, respectively. Furthermore, due to the close spatial proximity of the bicycle to the building and, by consequence, the smaller angle between the bicycle and the building, the wireless signal is impacted by the lateral movement of the cyclist. During recording of the traces, we observed that the cyclists were usually moving closer to the road than to the building. As a result, the variance in this position among the traces (i.e., among iterations and cyclists), leads to a larger distribution of the recorded warning time values in comparison to the scenarios 301 and 302. Still, wireless communication allows both vehicles to recognize each other up to 1785 ms and 2679 ms in advance of being within LOS of each other.

In essence, even though only a simplistic beaoning protocol is employed, our measurements not only show that communication is beneficial (giving cars and bicyclists the ability to recognize each other well before being within LOS of each other), but illuminate the nature of dependence on velocity, beaoning frequency, and transmit power for safety messages.

V. CONCLUSION

In this paper, we investigate the need for more realistic modeling of cycling behavior for studies of Advanced Driver Assistance Systems (ADAS) supporting not only drivers but particularly also Vulnerable Road Users (VRUs). Our focus is on the interaction between cyclists and cars at intersections, emphasizing on scenarios which have been reported to be the most safety critical situations. We selected an empirical approach for modeling the cyclists' behavior and to integrate the resulting models into a well established vehicular networking simulation platform. For this purpose, we developed our Virtual Cycling Environment (VCE), which allows participants to cycle in a virtual environment sitting on and interacting with a real bike but using Virtual Reality (VR) concepts for modeling the environment. We recorded numerous traces, which we, in addition to the VCE, make available to the research community as Open Source. We used the traces for a first proof-of-concept experiment showing that vehicular networking based assistance systems substantially help increasing the time between notification and possible crash.

In conclusion, we see our VCE platform as a first step towards a novel generation of studies (a) from a cognitive psychology perspective trying to better understand cycling behavior, and (b) from an engineering point of view developing novel ADAS for VRUs. Next, we will use the VCE for interactive studies in combination with V2X communication.

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