V2X-based cooperative protection system for vulnerable road users and its impact on traffic

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Abstract

Vulnerable road users like cyclists and pedestrians are endangered by motorized vehicles, especially at signal controlled intersections. This approach presents a protection system consisting of communication devices and an infrastructure solution. While vehicles can be equipped with V2X modules, cyclists and pedestrians can distribute their movement data via mobile devices like smartphones with GNSS and Wi-Fi capabilities. A roadside unit collects the data, predicts collisions and warns (only) the affected road users via appropriate digital messages. The paper describes the collection of data, positioning improvement, collision prediction methods and how the impact on traffic can be estimated. The protection system also was implemented prototypically as a working demonstrator.

Keywords:

V2X, Vulnerable Road Users, Road Safety, Cyclist Protection, Mobile Applications

1 Motivation

Vulnerable road users (VRUs) like cyclists and pedestrians are generally endangered by motorized vehicles. Especially at signal controlled intersections where they both have a green light and paths are crossing, vulnerable road users are overlooked easily (Figure 1). In several cities around the world, you can find "Ghost Bikes" that are both memorial for crashed cyclists and to indicate dangerous intersections (1).

Figure 1 – A vehicle endangering a cyclist

Figure 2 – Signal indicating possibly crossing VRUs

A common and “unintelligent” solution is a signal that blinks so that vehicle drivers pay attention (Figure 2). But because this signal is active at each green phase, independent from real cyclist traffic, a habituation effect acts on drivers. To create a situation-aware solution, more and more vehicles are equipped with sensors to analyze their environment themselves and to feed driver assistance systems. But such detection systems only rely on the data that can be gathered from their point of view.

Cooperative systems offer additional benefits: Data can be gathered from other road users or via roadside sensors and shared via wireless communication. The vision is to integrate more and more road users into cooperative, Intelligent Transportation Systems (C-ITS). This paper describes corresponding work, done within the German joint research project UR:BAN (2), mainly incorporating V2X communication.

2 Technology and known research for VRU protection

The protection of human life in traffic is a matter of safety. Since the beginning of the 21st century, the technical development concentrates on active safety solutions, called Advanced Driver Assistance Systems (ADAS). One example is the collision detection assistant. Obstructions are detected via internal sensors, like radar, LIDAR and cameras. Drivers are warned, or the vehicle even brakes automatically. In these cases, the system is called Autonomous Emergency Braking (AEB). By regarding especially the algorithms that detect pedestrians, we talk about Pedestrian Auto Emergency Braking.

A new approach is the connection of vehicles and VRUs. The idea is that one can inform the other via wireless communication to trigger warning actions. One example is the communication between cars and a special bicycle helmet, developed by Volvo, POC and Ericsson (3). Volvo cars and the helmet are connected via internet. They share position data and warn each other when a collision is possible: Drivers via their head-up display, cyclists through a helmet-mounted alert light.

The main problem with such proprietary solutions is always the equipment rate. Cyclists must want to wear a bicycle helmet in general. Then, they need this new model with networking and warning abilities. Rather an open standard is needed that is developed by several stakeholders from the start to fit everyone’s needs.

From 2013 to 2016, the European VRUITS project (4) took a VRU-centric approach to come to recommendations for ITS applications aimed at improving the safety, mobility and comfort of VRUs. The aim was the full integration of the VRUs in the traffic system. The main research areas were societal impacts of selected ITS as well as HMI designs to meet the needs of VRUs. Here, the cooperation via vehicle to vehicle and vehicle to infrastructure communication (V2X) has already been discussed, but no implementations have been done.

With V2X, the standardization of communication between road users and infrastructure has begun. Special protocols are used to share data between equipped road users. The IEEE has standardized it as IEEE 802.11p as an extension of the Wi-Fi standard. The European

Telecommunications Standards Institute (ETSI) reserved the 5.9 GHz frequency band for applications of intelligent traffic systems (ITS) within Europe. Furthermore, specific message formats have been developed. The most important are CAM (Cooperative Awareness Message) for status messages of road users, DENM (Decentralized Environmental Notification Message) which can be used for warnings, SPAT (Signal Phasing and Time) which gives information about traffic lights and TOPO (Topology Message) which offers details about an intersection's topology.

Currently, new driver assistance systems which use these messages are under development. One example is the Green Light Optimal Speed Advisory (GLOSA). But ADAS that use V2X to incorporate VRUs are not known, yet. To provide a prototypical solution of protecting vulnerable road users via C-ITS and V2X, the institute ifak for applied research developed the so-called cyclist protection systems. This paper describes details of the research, the technical implementation as well as the developed demonstrator.

3 Use cases and system architecture

Within the focus of this work are situations where vehicles endanger vulnerable road users because of the traffic light situation: At many urban, signal controlled intersections, turning vehicles and VRUs have green at the same time. In general, there are two main use cases, depicted in Figure 3: Either right turning or left turning vehicles may overlook a cyclist who has right of way.

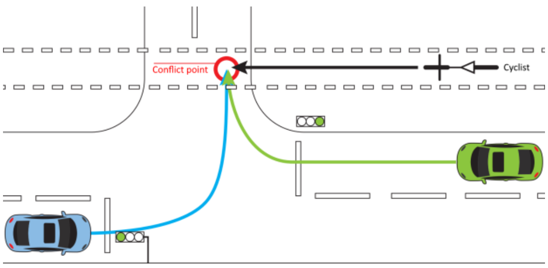

Figure 3 – The two main use cases where vehicles endanger VRUs

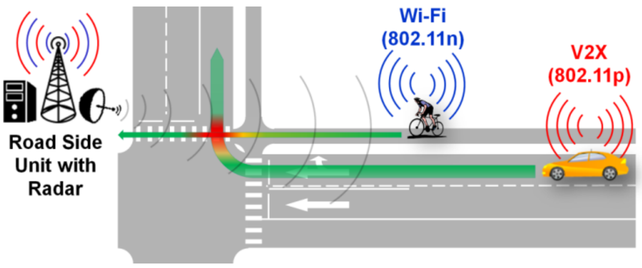

Figure 4 – General overview of the protection system; predicted conflict area in red.

The presented protection system is a cooperative solution, based on communicating road users and infrastructure. The potential of the new V2X technology shall be used. Therefore, it is assumed that vehicles will be equipped with IEEE 802.11p communication units (WLANp CCUs). They send status data cyclically via cooperative awareness messages (CAMs). Also, they must be able to receive and compute decentralized environmental notification messages (DENMs) which shall be used to warn of crossing VRUs.

Unfortunately, the current development of 802.11p focusses solely on motorized vehicles, so that there is currently no mobile 5.9 GHz 802.11p device available for road users like cyclists and pedestrians. But many people carry devices like smartphones which are capable of

“normal” Wi-Fi, i.e. IEEE 802.11a/b/g/n in the 2.4 GHz or 5.2 GHz band, respectively.
To incorporate these devices and therefore VRUs into an intelligent traffic system, an infrastructure solution was chosen as a mediator. It is a Roadside Unit (RSU) that is capable of 802.11p as well as standard Wi-Fi, like shown in Figure 4. One advantage of this infrastructure solution is that additional sensors can improve position data and even detect road users that are not equipped with V2X CCUs or smartphones, respectively. For the presented project, advanced radar sensors where chosen. Another possible benefit is that the collected data about road users crossing an intersection could be used to feed further driver information systems or statistics. The connection between outstations like RSUs and traffic control centres currently uses proprietary protocols, which is targeted by standardisation efforts like OCIT (5).
The roadside unit consists of an application unit (AU) which runs the core protection application. It gathers movement data of detected road users, predicts collisions and warns effected road users. Eventually, such a protection system shall integrate seamlessly into the pool of applications that is planned to be offered at V2X-enabled urban intersections.

4 Integration of vehicles via V2X/11p

One idea of cooperative ITS is that road users can share information wireless. To share status data cyclically, *Cooperative Awareness Messages* (CAMs) have been standardized. They incorporate position, speed and other parameters, according to the used station profile. Vehicles shall be equipped with 802.11p communication units (CCUs) that send CAMs cyclically, most probably between one and ten Hertz. One advantage of 802.11p is that messages can and shall be sent as a broadcast, without the need of a base station, in opposition to current mobile radio networks like 4G/LTE. Therefore, every 802.11p CCU within reach can receive such status data. Eventually, the protection system incorporates an 802.11p CCU to listen to vehicle CAMs to track their movement data. The aim is to estimate the time that a vehicle needs to reach the observed intersection.
A CAM’s payload carries the *referencePosition*, given as latitude and longitude in the WGS-84 coordinate system. This is the first important parameter. For position measurement, the vehicle itself or the V2X CCU have a built-in sensor for the *Global Navigation Satellite System* (GNSS). By using other sensor data, e.g. the wheel speed, the GNSS position can be improved, e.g. in tunnels (dead reckoning). Therefore, the protection system can expect already improved position and movement data from CAMs.
According to the used *ITS station profile* (6), some parameters are mandatory while others are optional. For private vehicles, the *basicVehicle* profile shall be used and offers the following mandatory parameters that are useful for the collision prediction algorithm: vehicle speed, heading and longitudinal acceleration.
In addition to that, the exteriorLights parameter contains a flag that indicates if a turn signal is set. This helps to decide if a vehicle is going to turn at the oncoming intersection and should

really be taken into consideration.

The profiles emergencyVehicle and publicTransportVehicle incorporate the same mandatory parameters (and demand some more). All in all, the protection system can assume that every vehicle with these profiles sends the necessary parameters to predict their movements.

Let’s assume a collision with a VRU at the intersection has been predicted. This information can also be brought to the effected vehicle(s) via V2X. The corresponding message format is called Decentralized Environmental Notification Message (DENM). In the presented project, a DENM is used to warn of collisions between vehicles and vulnerable road users for the first time within a working demonstrator. The following parameters are considered the most important and have to be set by the protection system:

- actionID: Unique ID to identify individual predicted collisions.
- cancelationFlag: To cancel a previously sent warning, e.g. when the collision criteria don’t meet anymore.
- causeCode (according to TPEC-TEC tables): to indicate different reasons of the warning. For the protection system, the value 30 (“people on roadway”) was chosen.
- subcause (optional): Value 2 for “cyclists on roadway”.
- locationRef: Can define the predicted collision point, i.e. the crossing.
- destinationArea: Defines the relevant area for the warning, which can be the whole intersection or just the effected lane.

Once the DENMs are received by vehicles, they must be computed and actions be carried out, either by informing the driver or by affecting driver assistance systems. One advantage is that DENMs and their cause codes are standardized. Developers of such a VRU protection system don’t have to supply information about the action to be carried out. This is left solely to the vehicle manufacturer.

5 Integration of vulnerable road users via smartphones and Wi-Fi

Currently there’s no proven concept or even standard to integrate vulnerable road users (VRUs) into cooperative ITS. The presented work presents a solution to achieve high equipment rates. Today, many people carry smart devices like smartphones which are capable of GNSS positioning as well as radio and Wi-Fi communication.

For the protection system it is assumed that a VRU that wants to be protected by the system carries a smartphone with a special app running on it. Cyclists even could attach the phone to their handle bar, like shown in Figure 5. The app gathers movement data via internal sensors. For the connection to the protection system’s roadside unit (RSU), Wi-Fi has been chosen within the demonstrator. The RSU offers an access point to which the smartphone has to be connected at least once so that SSID and password are stored.

If the user approaches the intersection and the signal gets strong enough, the device automatically logs into the network and the app starts transmitting status data cyclically.

Within the project, an Android app was developed with the Qt C++ framework (7). This has the advantage that it can build programs for a desired target platform, e.g. Android, iOS and Windows Phone which all have different native programming languages.

Theoretically, the V2X formats for CAM and DENM could be used to structure the data. But the overhead would be quite large because just a few values are needed. Eventually, an own data format has been defined to transmit information via Wi-Fi UDP packets. Just these parameters are transmitted cyclically from the mobile device:

- Position (latitude, longitude in WGS-84)
- Speed
- Longitudinal acceleration
- Heading

Figure 5: Smartphone with protection app mounted to bicycle handle bar

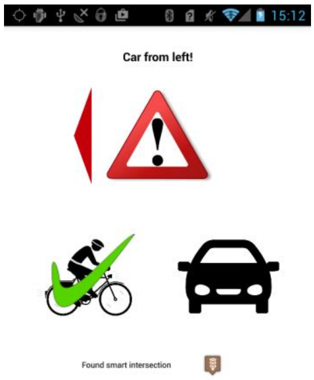

Figure 6: Mobile protection app warning of an approaching vehicle

The source of the position data is the satellite navigation system (GNSS), like GPS. To remove outliers, a low pass filter is applied. Further improvement could be done by mapping to position against a street map, like several map apps do it already. Eventually, the position and speed data from the low pass filter was accurate enough in the first field tests to estimate the time a VRU needs to reach the intersection.

If a collision has been detected, also a UDP packet informs the VRU about it. It contains a unique ID and the position of the danger so the direction can be calculated and presented to the user.

In the end, the warning is presented on the screen (Figure 6), via an alarm sound and vibration. In addition to that, several alternatives have been evaluated to warn VRUs. With the help of the 3D game engine Unity, an interactive simulation has been implemented. A test user can ride a virtual bicycle trough a simple urban area. At some intersections, they are warned of turning vehicles. In addition to the smartphone, a vibration wristband (own construction) and even data glasses (Epson Moverio BT-200) have been evaluated. Figure 7 shows the results of a corresponding survey on how users would accept the different warning devices.

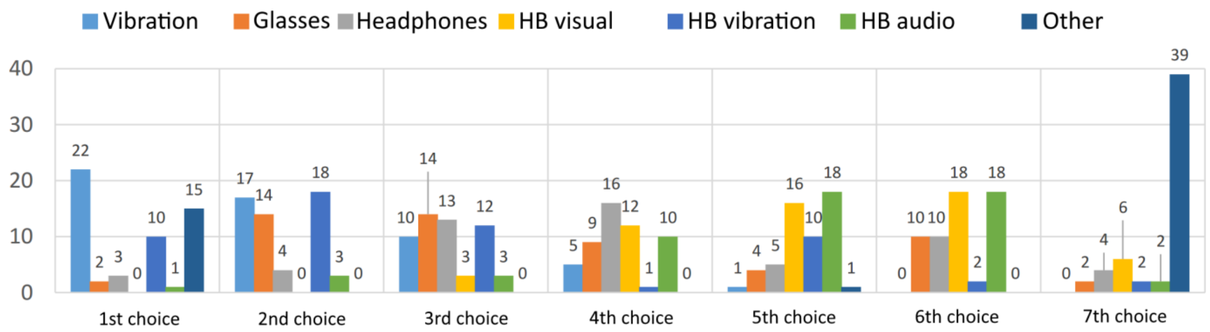

Figure 7 – Results of a survey on most favoured warning methods

Surprisingly, many users didn't prefer the smartphone solution, mounted to the handlebar (HB visual). The most favoured solution was the vibration wristband. As a conclusion, vibrating smartwatches could be a good device to convince VRUs to use such a protection system in the future.

6 Improvement of position detection via radars

The assumption that vehicles have 802.11p CCUs installed and VRUs carry smartphones with an appropriate app is critical for the operation and success of such a protection system. To also detect unequipped users, additional sensors can be installed and connected to the application unit. This offers two advantages: Firstly, they detect those road users that are not capable to tell their position via any wireless communication. And secondly, GNSS position data of equipped road users can be improved.

Cameras are one possibility. But firstly, procession of video data needs quite some computing power which would raise the costs of an appropriate and powerful RSU. Secondly, such optical sensors can get dirty quite easily and therefore need regular maintenance. And thirdly, the acceptance of cameras in public space can be quite low, for privacy reasons. Therefore, radar sensors have been evaluated as an alternative. Because only approaching road users matter for collision detection, one sensor for each intersection approach suffices.

For the presented project, an *UMRR sensor* from Smartmicro (8) has been chosen and installed at some urban research intersections in Germany. In fact, this device consists of several sensors within one housing to measure different parameters of obstacles, like their speed. It combines the measurements and supplies them in an already interpreted form. The protection application does not need to compute image data or the like. By connecting the sensors to the application unit (AU) via Ethernet and setting up a TCP server, all UMRR radars connect automatically and send their object detection data cyclically to the AU. Thus the protection application on the AU can work with the following values:

- Object ID: The radar already tracks individual objects when they come in sight and reassigns this ID not before the object has left the field of view.
- Length: Also indicates the classified object type, e.g. always 2 m for a cyclist
- Range: Distance from the radar installation point.

- Speed

Figure 8 shows the fields of view of four of such radars, installed at an intersection with four approaches. Initially, all detected objects are saved as independent road users. In a new collision prediction cycle, these radar objects are compared separately to vehicles and vulnerable road users (GNSS objects) which were detected via wireless communication. Now, three cases are possible, which are also presented in **Figure 9**:

- Within a certain radius to a GNSS object, there is *only one* radar object.
- Within a certain radius to a GNSS object, there is *more than one* radar object.
- Within a certain radius to a radar object, there is no GNSS object.

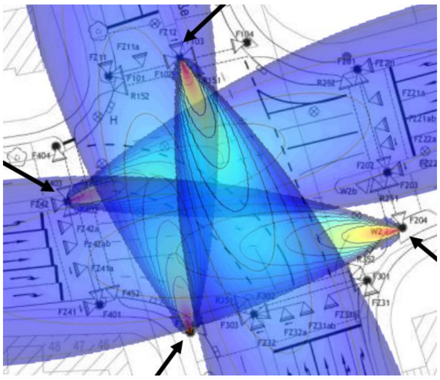

Figure 8 – Radar positions and field of views

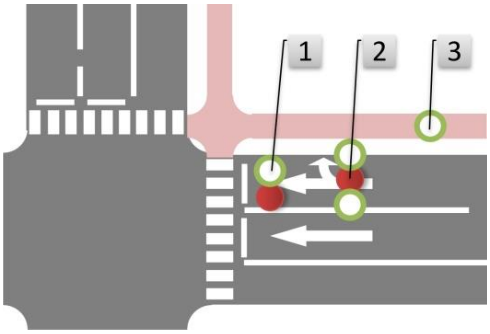

Figure 9 – Different cases of road user detection: by V2X communication (full red circles) and radar (green hollow circles)

When there is only one object within a certain radius, they are probably the same physical objects (case 1). The GNSS position can be corrected with the radar position, according to a reliability factor. This determines which position determination method is more reliable. For a first implementation, 0.5 was chosen to set the new position right between the two old ones. Alternatively, it could be something like 0.9 if the radar was far more reliable than the GNSS position measurement.

When there are several radar objects near a GNSS object it is difficult to determine which belong together (case 2). In this case, no correction occurs. It couldn’t be determined in which direction and with which factor these points should be weighted.

After all GNSS positions have been corrected by available radar data, there still can be radar objects with no corresponding GNSS object (case 3). Probably these are unequipped road users. The position determines if they are on the road or the bike path and this way their type is identified. These objects will be added to the list of vehicles or vulnerable road users, respectively. Their positions can be still used to predict collisions and to warn equipped road users. E.g. in Figure 9 for case 3, the radar has probably detected a cyclist on the bike path. A disadvantage is that only speed and acceleration data are directly available via radar. Acceleration and heading must be calculated by the application unit, if needed.

7 Collision prediction

With position, speed, acceleration and heading, the current trajectory of a road user can be calculated. This gives the information at which time the intersection will be reached.

The first thing that has to be done is to make the position data comparable. V2X CAMs and Wi-Fi TCP packets carry position data given with longitude and latitude. But the radar sensors have their own, local Cartesian coordinate system with X and Y axes. V2X topology messages (TOPO) are the exemplar for the chosen solution: They define a Cartesian reference point for an intersection. This is also used by the VRU protection system's core application, running on the roadside unit. The reference point once was measured with high precision and is given with longitude and latitude. The same is done with the radar sensor positions and their angles in relation to the WGS-84 system. This way, the radar object positions can be transformed for the reference system. Also, the GNSS object positions (from CAMs or Wi-Fi) can be transformed into this system.

Because only turning vehicles pose a danger, this must be predicted, too. If there is a lane that is solely for turning vehicles and a vehicle is matched against it, it can be assumed that it will turn if it stays on this lane. In addition to that, the turn signal status flags within a V2X CAM can be used.

Another standardized V2X message format is Signal Phase and Time (SPaT). It consists of the current signal of a traffic light and the estimated switching time. Manufacturers plan to generate these messages directly within V2X enabled traffic lights in the future. This message or a directly attached traffic light control could give the protection system the information if vehicles and VRUs of one approach have a green light at the same time.

With the gathered movement data, the protection system's central application can predict possible collisions. This is done by calculating the *Time to collision* (TTC) of every possible vehicle-VRU pairing. In this case, the TTC is the time needed to reach an intersection's crossing where the trajectories of both types of road users are going to meet. A simple estimation can be done when a road user's speed v is almost constant:

$$TTC = t = s/v$$

The distance s is the distance between the current position and the crossing.

A collision is assumed if the differences of both TTCs go below a certain threshold. For the prototype, three seconds have been chosen. A good threshold still needs to be determined experimentally.

To refine the collision prediction, several challenges have to be tackled. One is tailback of vehicles. If the traffic light is red and several vehicles wait in line, they will need some time to accelerate when the light turns green. This increases their individual TTCs, according to their position in the queue. This can be detected by sensors like the radar.

According to the German FGSV's guideline (9) (10), approximately two seconds pass for the start-up of every vehicle. With the distance to the stop line d_{SL}, the length of a vehicle l_V and the distance between two vehicles d_V, the delay $t_{tailback}$ (in seconds) for the start-up of a certain vehicle can be estimated:

$$t_{tailback} = \frac{d_{SL} \cdot 2s}{l_V + d_V}$$

8 Prototype and demonstration

Within the UR:BAN project, a working demonstrator has been implemented. It has been tested at research intersections in the cities Braunschweig and Düsseldorf. The scenario was that both a right turning vehicle and a cyclist approach an intersection.

The first field tests aimed for a working communication chain. The chosen 2.4 GHz Wi-Fi access point turned out to be problematic at urban intersections where already many private access points exist. The login of a smartphone of an approaching cyclist occurred to late so that his movement couldn't be considered by the protection system. As a solution, a 5 GHz antenna (and compatible phone) was used where the channels aren't that overcrowded, yet. In return it had to have a higher gain to compensate to loss of range that comes with a higher frequency.

A demo vehicle was equipped with an 802.11p device. The 5.9 GHz V2X antenna as well as the GNSS receiver where attached magnetically to the roof. It would have been quite complicated to pass on the warning from the vehicles 802.11p CCU to the HMI via the CAN bus. As an alternative, a smartphone was attached to the windshield. The vehicle's 802.11p module was in fact a computer that could also provide a Wi-Fi access point to which the smartphone was connected. When a DENM was received, a UDP packet was transmitted to the phone automatically. Here, the same app could be used that was already utilized to warn cyclists from their handlebar. This happens by choosing a role. For VRUs, status data is sent to available roadside units and users are warned of crossing vehicles. If the role of a vehicle driver is chosen, no status data is sent. In turn, users are warned of crossing cyclists.

In general, the developed demonstrator worked well for the regarded use case of a right turning vehicle and a cyclists approaching from the same direction. Within 60 m, the cyclist could send status data via Wi-Fi. The vehicle's V2X CAMs could be received within 150 m distance from the roadside unit. Both road users where detected by the radar within 100 m. All in all, the time suffices to predict collisions. Only the detection algorithm still needs some improvement. The use of the static speed and distance formula still was too susceptible to measuring inaccuracys. Therefore, a more robust version has been implemented as an alternative where only the distance to the intersection is considered. For a future version, the decision on sending warnings could be separated into several steps, from using the current speed and acceleration (far distance) to just using the distance.

9 Impact on traffic

Within the presented project, traffic simulations have been carried out to estimate the impact of such a protection system on safety and traffic flow. To compare different scenarios, indices are necessary.

The first *safety index* is the *time to collision* (TTC). Generally it is defined as the time until two road users collide (11). For the protection system it was redefined. The collision point is an intersection's crossing where two road users will be at about the same time. So the time to collision is the time one of the individuals needs to reach that point. These times and their differences are calculated for every possible pairing. Only when the difference is within a certain threshold, both road users are expected to be too near when reaching the crossing. This is classified as a dangerous situation and the effected road users must take actions to prevent a collision, which is altering their speed. Because at signal controlled intersection, generally vulnerable road users have right of way, vehicles have to slow down to affect their TTC.

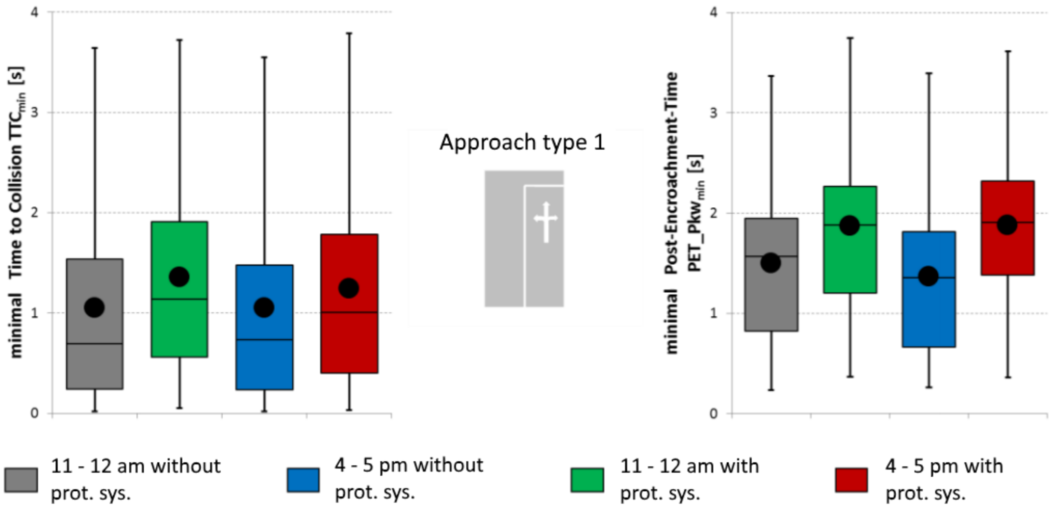

Figure 10: Effect of the VRU protection system on TTC and PET

Therefore, a traffic simulation, carried out with VISSIM from PTV, emulates the protection systems in the following way: Vehicles and cyclists are simulated at several signal controlled intersections (number and type of lanes vary). When both a vehicle and a cyclist approach the intersection, the normal behaviour algorithm would stop the vehicle not before reaching the crossing to prevent a collision. Microscopic traffic simulations like VISSIM or SUMO can't even simulate collisions naturally. In the scenario of an active protection system, a new behaviour has been implemented so that the vehicle notices the cyclist earlier and slows down to adjust its TTC so that no stop at the crossing will be needed. The increased TTC for a simple intersection approach (type 1) is depicted via a box-and-whisker plot on the left side of Figure 10. The simulation has been carried out for two different times of a day, with less traffic (11 – 12 am) and more traffic (4 – 5 pm). Equipment rates of 0 % (no protection system means no early decelleration) and one of 100 % (always early decelleration) have been compared.

Another parameter to evaluate the resulting impact on traffic safety is the *post-encroachment time* (PET). According to Allen (12), this is the time between the first road user leaving the common spatial zone and the second arriving at it. Laureshyn et al. (13) extend the concept of the PET by calling it *time advantage*: It is determined at every time step, because the (static) PET can change by influences like the protection system. The PET or time advantage is a better impact indicator than the TTC, because it also exists when no collision is imminent. A higher value indicates more space between possible collision partners and therefore a safer traffic scenario. The right side of Figure 10 depicts the simulated effect of the protection system on the PET for approach type 1. One can clearly see that also the PET increases. In comparision to other simulated aproach types, those had the best results that have an own lane for right turning vehicles.

Secondly, the impact on traffic flow has been simulated. The criteria are travel speed and travel time. Because an early slow down of vehicles is asumed, the travel time increases with an active VRU protection system. Assuming an equipment rate of 100%, the time to pass an intersection increases about 10 %. But this is only in cases where a cyclists approaches, so this loss of traffic effiency to increase safety should be accepted.

10 Summary and future work

This paper presented a protection systems for vulnerable road users, using technology of cooperative ITS. Vehicles are detetced by V2X CAMs and VRUs via a smartphone app and Wi-Fi. A roadside application unit computes the movements and sends warnings via wireless communication of a collision s predicted. The existing standard of V2X CAMs and DENMs already provides all the necessary parameters.

Regarding statistics on how many people carry mobile phones and by expecting that every car will have wireless communications in the future, the feasability of the presented protection system is not really a question of equippment rates. It rather is a question of the technical solution to integrate such a protection application into a widely connected future world, e.g. within the context of Internet of Things (IoT) (14).

Improvements could be done for the poistioning via satellites. E.g, with the roadside unit, its precicely measured position and an own GNSS sensor, correction data could be sent to road users to improve their positioning via *differential GNSS*.

Also, further research could be done for an ideal way to warn vulnerable road users, e.g. by incorporating vibration in several ways and finding portable technical solutions.

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