Vulnerable Road Users Are Important As Well: Persons in the Collective Perception Service

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***Abstract*—Vulnerable Road Users, such as pedestrians and cyclists, are a significant proportion of all traffic participants but have limited capabilities to protect themselves in accidents. Hence, raising awareness of their presence among vehicles is vital. One key technology in this regard will be the Collective Perception Service (CPS), which is currently standardized by the ETSI. It enables vehicles to exchange information about locally perceived objects via Collective Perception Messages, improving situational awareness and allowing perception of obstructed traffic participants. However, the CPS distinguishes vehicles and person-type objects when generating messages because of their difference in movement patterns and dynamics. This paper analyzes the inclusion rules for person-type objects in a large-scale simulation study, showing that the CPS can significantly improve awareness of persons with little additional channel resource usage. Finally, alternative parameterizations for the CPS are analyzed, indicating how different tracking accuracies for persons can be achieved.**

I. Introduction

The avoidance and severity reduction of road casualties are still among the key motivations for the ongoing research and development of vehicular technology in order to achieve *Vision Zero*. In the past, vehicles were made safer with mechanical improvements, such as seat belts, Anti-lock Braking System (ABS), and improved body design to reduce the impact of collisions for passengers as well as other involved parties outside the vehicle. Until recently, the safety of a vehicle, its passengers, and its vicinity was entirely in the operator's hands. But with the increase of computational power and the development of new sensor technologies, several Advanced Driver Assistance Systems (ADASs), such as the Emergency Brake Assist and the Blind Spot Monitor, were developed and introduced to the production of vehicles. Vehicles providing these functions can perceive their surroundings using various sensors and determine potentially dangerous situations. In these, the vehicle takes over the control to either reduce the impact or even mitigate accidents entirely.

For further improvements of vehicular perception beyond the range of local sensors and, thus, a better understanding of the surrounding traffic situation, Vehicle-to-Everything Communication (V2X) is currently under research, development and standardization. The first message types, such as the Basic Safety Messages (BSMs) in the U.S. and its European equivalent, the Cooperative Awareness Messages (CAMs), focus on vehicles, sending their kinematic state via broadcast to inform others of their existence. But these messages only enhance the receivers' perception by the presence of other modern, communicating vehicles. This limits the impact of these messages, especially in the early adoption phase of vehicular communication, which is currently proceeding in Europe with roll out of Volkswagen's Golf Mk8 and ID.3 To overcome this limitation, the European Telecommunications Standards Institute (ETSI) investigated Collective Perception (CP) in the Technical Report (TR) 103 562 [1] and is currently drafting the standard for the Collective Perception Service (CPS) and the corresponding Collective Perception Message (CPM) [2]. With the CPM, vehicles periodically broadcast a subset of self-perceived objects from their Environment Model (EM), as well as their perception capabilities. Receiving vehicles are then able to enrich their EM with information about non-communicating traffic participants, improving their overall situational awareness, bridging the gap between communicating and non-communicating vehicles.

However, besides vehicles, also animals and Vulnerable Road Users (VRUs), including Powered Two-Wheelers (PTWs), bicyclists, pedestrians, persons in wheelchairs, with strollers or on skates are considered in the CPS [1]. VRUs are deemed important since these will most likely not be able to communicate with vehicles to announce themselves in the near future, due to many unresolved issues, such as a common communication interface or the accuracy and precision of localization technologies for user equipment. Furthermore, they are in a very disadvantageous position from a safety perspective and, hence, of utmost importance for general traffic safety. According to the Car2Car Communication Consortium (C2C-CC), CPS has a great potential to reduce potentially fatal accidents with VRUs [3]. But due to their distinct movement pattern, objects classified as person, e.g., bicyclists, pedestrians, and animals, are handled very differently in the CPS as other vehicle-type objects. As a consequence, the classification of the object determines when these objects are included in a CPM. However, only the rule set for vehicles was analyzed in various studies, while the inclusion rules for persons and their configuration did not get any attention in research so far.

This paper contributes a detailed analysis of the inclusion rules for persons as described in the current TR for the CPS by the ETSI. It evaluates the effect of the separate rule set on channel congestion, information recency, and awareness for person-type objects, as well as its impact on vehicle-type objects. Furthermore, it presents an analysis of an alternative configuration for the inclusion rules. Therefore, we present related work in the field in Section II. The CPS, the message generation, and the object inclusion process are described in Section III. Section IV describes the setup of the simulation study, the simulation framework, as well as the scenario. In Section V, the impact on the communication channel and awareness is analyzed. Finally, we conclude our analysis in Section VI and give an outlook for future work.

II. Related Work

From a technical perspective, VRUs have very limited capabilities to protect themselves in case of accidents. Hence, protection mechanisms are integrated into more potent road users such as vehicles and trucks. As an important step towards the reduction of road fatalities among pedestrians, the European Commission (EC) funded the *Advanced Protection Systems* (APROSYS) project in which means for passive safety mechanisms were developed, such as improvements to the hood and bumper designs to reduce the severity of accidents [4]. Later, the EC approved regulations that require car manufacturers to equip their vehicles with passive safety mechanisms to acquire type approval [5], [6]. Additionally, the New Car Assessment Program (NCAP), which assesses and rates the safety of vehicles, has integrated test procedures for VRU safety in its rating process to create an incentive for manufacturers to improve their VRU protection mechanisms even further.

Further advances in research and development focus more on the pre-crash aspects of VRU protection to either deploy safety mechanisms before impact or completely avoid the collision. Therefore, vehicles are equipped with sensors to detect and classify VRUs [7] and predict their movement behavior to determine dangerous situations [8], [9]. However, onboard sensors, such as Radar, Lidar, and camera, are limited in their perception capabilities since their field of view can be obstructed by other objects, hiding VRUs in potentially dangerous situations. Additionally, their classification, depending on the information quality, can be erroneous, and hence, other sources of information are explored as well.

To overcome these limitations, the WATCH-OVER project [10], co-funded by the EC, explored not only the detection of VRUs but also different communication technologies for direct communication between VRUs and vehicles. Received data was then used by the receiving vehicles to detect potentially dangerous situations, warn the driver accordingly and, thus, enhance safety for all traffic participants. While direct communication can be feasible in theory and practice, there are barriers to mass deployment since VRUs need to carry User Equipment Devices (UEDs) with means for precise localization and a compatible communication interface.

Morgenroth et al. suggested further mechanisms to increase awareness where vehicles get informed about dangerous situations involving pedestrians using wireless communication [11]. One of their approaches suggests the localization of pedestrians using Ultra Wide Band (UWB). While pedestrians carry a UED, vehicles are equipped with two UWB radios on their front bumper, enabling triangulation of the UED to determine the relative position of the pedestrian. Furthermore, they suggest using Road Side Units (RSUs), capable of communicating with pedestrians using UWB and with vehicles via IEEE 802.11p. While pedestrians and vehicles broadcast their current position, the RSU calculates potential collisions based on the received positions and sends out warning messages when critical situations are detected. These approaches do not require a common communication interface. However, infrastructure components need to be deployed and maintained, which is costly on a large scale.

Lately, communicating VRUs are also well-considered in the standardization of Cooperative-Intelligent Transportation Systems (C-ITS). The Society of Automotive Engineers (SAE) standardized the Personal Safety Message (PSM) in J2945/9 [12] and ETSI released the specification of the VRU Awareness Message (VAM) and the respective service [13]. These messages lay the foundation for direct communication between VRUs and vehicles in the case where the VRU can determine its kinematic state and announce itself. However, also indirect communication is considered, where a vehicle or RSU detecting the VRU can emit a message to raise awareness and support safety applications. Along with the standardization of the message formats and the potential for widespread utilization, the impact on the vehicular network's performance is an upcoming research topic. Therefore, implementations for communicating VRUs in popular vehicular network simulation environments [14] and studies for different message dissemination concepts were published [15].

But similar to the introduction of communicating vehicles to the market within the next decades [16], also the introduction of UEDs, capable of communicating directly with the increasing amount of communicating vehicles, will only pick up pace slowly. Additionally, and analogous to vehicles, not every VRU in the future will be capable of communicating at all and, thus, cannot benefit from this form of communication. Hence, the introduction of the CPS is as vital for VRUs as it is for vehicles [1], bridging the gap between communicating and non-communicating traffic participants. As Shan et al. demonstrated and simulated [17], the CPS allows vehicles to track obstructed persons, yielding safety benefits by reducing the detection time in several small-scale situations.

For larger scenarios, several studies have analyzed the network and awareness aspects of the CPS [18], [19], [20], [21], but only vehicle-type objects were considered so far. However, the dissemination rules for person-type objects are different from vehicle-type objects. Hence, their impact on network characteristics and awareness on a larger scale is still an open research question.

III. Persons in the Collective Perception Service

The CPS is part of the service set for day-2 vehicles [22]. Its goal is to further improve the overall situational awareness of connected traffic participants. Therefore, information gathered with local sensors is shared with others by transmitting that information through CPMs. This is done in the form of interpreted data, i.e., a list of perceived objects is shared rather than raw sensor data. That object list can include information about the current position of the objects, their speed, heading, dimensions, etc. Recipients of CPMs can enrich their EMs with the received information and then make better driving decisions.

Currently, there are no production vehicles with a CPS available on the market. However, standardization has come a long way already. In 2019, ETSI published an informative analysis of the possible functionality of the CPS in TR 103 562 [1]. Currently, the normative Technical Specification (TS) 103 324 [2] is under discussion and preparation.

Key use cases for collective perception are listed in the TR, and they explicitly mention the goal of increasing awareness about persons. A person is defined as either a pedestrian, a person in a wheelchair, a bicyclist, a person with a stroller, a person on skates, or a group of pedestrians in the document. This definition is also used throughout this paper. Crucial for the effectiveness of the CPS is the decision when to include which of the locally perceived objects into a newly generated CPM. From an application standpoint, it would be optimal to receive updates about the objects very frequently. Unfortunately, too frequent transmissions can easily overload the channel, and, therefore, inclusion rules were developed that provide recent enough updates for applications while not wasting channel resources. These inclusion rules are different for vehicular objects and person/animal-type objects and have not been changed since the release of the TR. For most types of perceived objects, inclusion depends on timing as well as dynamics of the respective object and an object is included in a newly generated CPM whenever it fulfills one of the following conditions:

1) The object was newly detected and not included in a CPM before.
2) The object moved by more than $4\,\mathrm{m}$ since it was last included.
3) The object changed its speed by more than $0.5\,\mathrm{m\,s^{-1}}$ since it was last included.
4) The object changed its heading by more than $4°$ since it was last included.
5) The object was last included in a CPM more than $1\,\mathrm{s}$ ago.

These rules are closely related to the generation rules of CAMs. The idea behind them is to include an object whenever it would generate a CAM if it were equipped with an Intelligent Transportation Systems-Station (ITS-S).

If the object is either an animal or a person according to the definition given above, those rules differ. Since these types of objects are expected to have a very different dynamic behavior than vehicles, their inclusion rules cannot be applied. However, this group of objects is still highly important from a safety perspective and, therefore, should be included in CPMs as well. Yet, this group of objects is very heterogeneous in its behavior. Thus, it is hard to find a set of optimal inclusion rules for each of those objects.

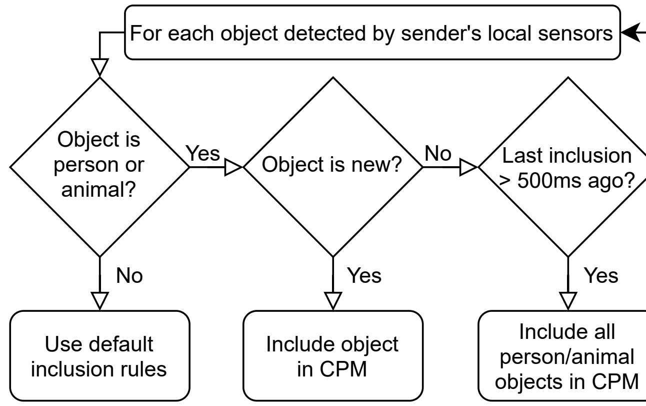

Fig. 1: Inclusion rules for objects of type person or animal currently defined in TR 103 562

Hence, [1] simply defines a purely time-based inclusion mechanism. As shown in Figure 1, all person-type objects known to the transmitter are included in a CPM whenever at least one of them has not been included in the past $500\,\mathrm{ms}$. When a new object of type person or animal is detected which has not been tracked before, it is directly included into the currently generated CPM. These rules are not justified in the documents, and neither is the value of $500\,\mathrm{ms}$ for the inclusion interval. To the best of our knowledge, there is no work analyzing the effects of those rules on the awareness they generate at the receivers. The additional channel load induced by the inclusion of persons has not been analyzed either but could be significant. This work rectifies that omission.

IV. Simulation

For the analysis of the object inclusion rules for persons on the network, as well as the impact on awareness, *Artery* [23] in combination with Simulation of Urban MObility (SUMO) (version 1.9.2) was used [24]. Artery is a vehicular communication simulator, which implements communication between vehicles according to the ITS-G5 standard [25] and integrates *Vanetza*, an open-source implementation of the ETSI C-ITS protocol stack. Additionally, it implements an environment model. It consists of the global EM, an object database containing vehicles and buildings along with their dimensions and freely configurable sensors, which can be attached to vehicles at different attachment points. With these sensors, vehicles can perceive objects within their surroundings and build up their local EM, depending on their sensors' perception capabilities and potential obstructions by objects. While SUMO already supports pedestrians, Artery did not handle pedestrians and, therefore, was extended to handle additions, deletions, and updates of pedestrians to the global EM, so that vehicles can perceive and include them in their local EM. Finally, the CPS implementation [26] was extended to handle objects of type person according to Section III.

As a simulation scenario, the Monaco SUMO Traffic (MoST) scenario was chosen [27] since it is one of the few large-scale scenarios that includes pedestrians and bicyclists. Due to the higher density of persons, the focus was set to the inner city of Monaco, neglecting the outskirts. Hence, only vehicles within the red-dashed boundary shown in Figure 2 were simulated with Artery. Additionally, parked vehicles had to be excluded due to the implementation of parking lots in MoST, where a single physical parking space could contain hundreds of vehicles stacked on top of each other. In the case of a sensor-equipped vehicle passing the lot, it was able to perceive all parked vehicles at the same time where they would cover each other in real life. This resulted in an unrealistically high amount of objects detected by the vehicles' sensors and, thus, huge CPMs.

After the simulation ran $60\,\mathrm{s}$ to let the Decentralised Congestion Control (DCC) settle, simulation results are recorded for $5\,\mathrm{s}$. Therefore, each equipped vehicle checks the objects inclusion rules of the CPS multiple times, generating between 5 and 50 CPMs. At the chosen scenario time of 9:15 AM (morning rush hour), the scenario contained 4244 vehicles (passenger cars, PTWs, emergency vehicles, $\ldots$) and 5252 persons (pedestrians and bicyclists). Since the scenario features many vehicle types, which are owned by different actors and offer different capabilities, different equipment rates (communication capabilities and sensors) were chosen for each of them. While state official vehicles, such as emergency, police, and army vehicles, are always equipped, ordinary vehicles in private possession, such as passenger cars, taxis, trucks, and buses, have a configurable Market Penetration Rate (MPR). PTWs, mopeds, bicyclists, and pedestrians are never equipped.

Equipped vehicles only run the CPS, while the Cooperative Awareness Service (CAS) is omitted to single out the impact of person-type objects on the channel.

In the simulation, V2X-enabled vehicles are equipped with two radar sensors to mimic the sensing capabilities of modern vehicles. The first sensor is attached to the front bumper with a Field of View (FoV) of $160\,\mathrm{m}$ with a $35°$ opening angle. The second one is attached to the rear bumper with an FoV of $80\,\mathrm{m}$ with a $325°$ opening angle. Therefore, equipped vehicles have omnidirectional perception with a range, similar to the perception capabilities used for the Telsa Autopilot [28].

For the simulation of the wireless transmissions, the Geometry-based Efficient propagation Model for Vehicle-to-Vehicle (GEMV2) [29] was chosen as the channel model to achieve a realistic channel load within the city center, since it can accommodate for obstacles, such as buildings and other vehicles, in the direct communication path as well as reflection and diffraction paths.

As a baseline, the simulation was run without including person-type objects at five different MPRs. For the evaluation of the inclusion rules for persons, the simulation was then repeated with person-type objects for the same MPRs. Lastly, the time threshold for inclusion of person-type objects (*personCpmGenInterval*), which is set to $500\,\mathrm{ms}$ in the standard, was varied to evaluate its impact on the network load and information recency. All other simulation parameters are shown in Table I.

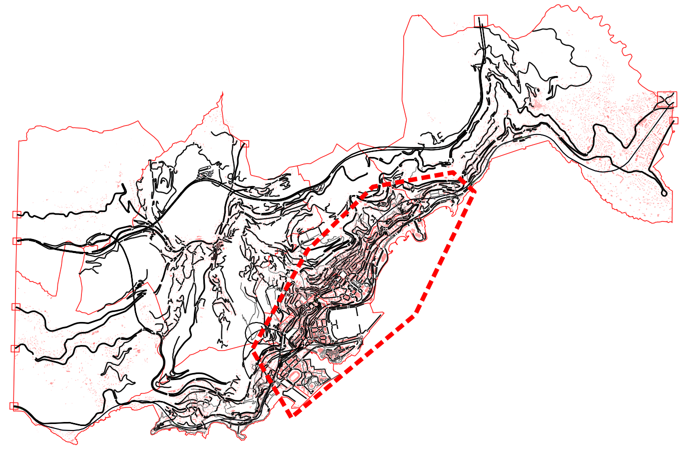

Fig. 2: Region of Interest in the MoST scenario used for the simulation study

TABLE I: Parameters of the Simulation Study

Parameter	Values
Access Layer	ITS-G5
Frequency	$5.9\,\mathrm{GHz}$
Transmission Power	$200\,\mathrm{mW}$
Channel Model	GEMV2 [29]
DCC	Adaptive (dual alpha) [30]
Persons enabled	true,false
MPR	10,25,50,75,100%
personTimeDeltaThreshold	$100\,\mathrm{ms}$, $\ldots$,$1000\,\mathrm{ms}$ in $100\,\mathrm{ms}$ steps

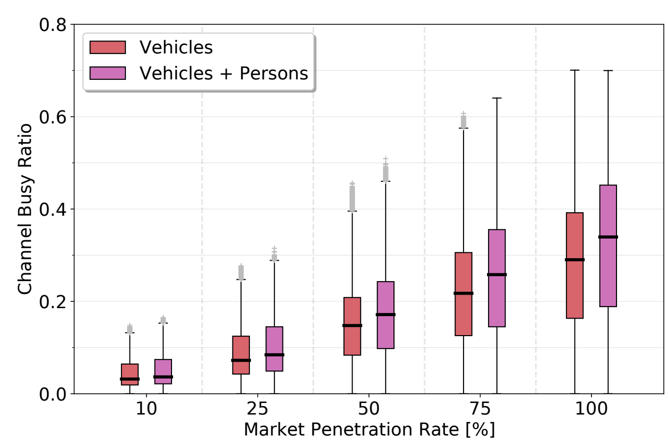

Fig. 3: Comparison of the Channel Busy Ratio (CBR) over different MPRs with and without the inclusion of persons using *personCpmGenInterval*$= 500\,\mathrm{ms}$

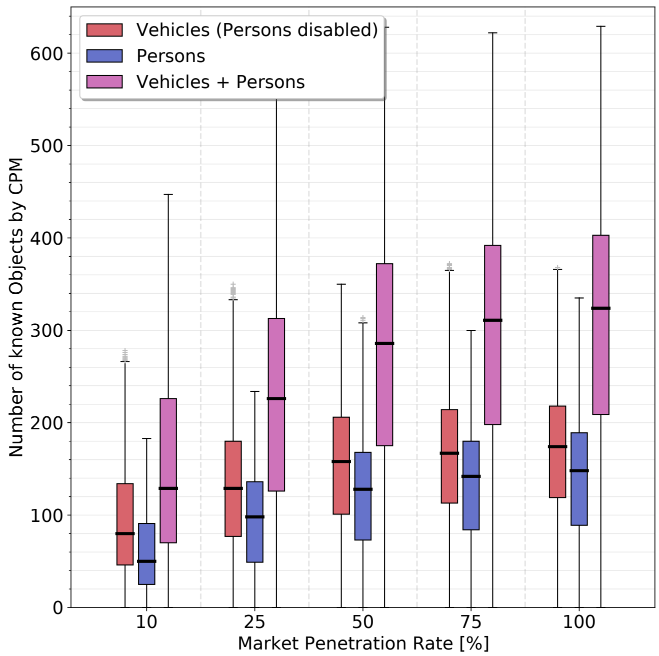

Fig. 4: Objects known by CPMs per vehicle grouped by object type over different MPRs with *personCpmGenInterval*= $500\,\mathrm{ms}$

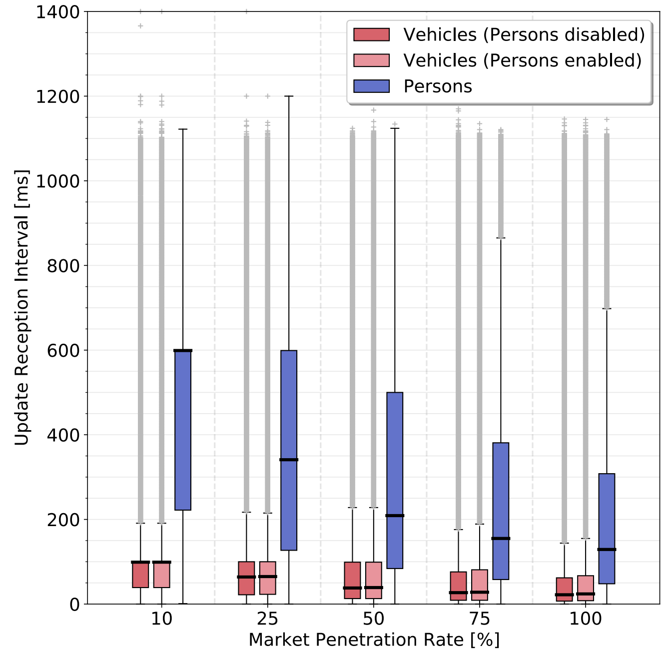

Fig. 5: Time between two consecutive updates for a single object aggregated over all vehicles and separated by object type with *personCpmGenInterval*= $500\,\mathrm{ms}$.

V. Evaluation

The first part of the evaluation investigates the influence of persons on channel and awareness metrics. In Figure 3, the aggregated CBR for all vehicles over the whole simulation duration is shown for different MPRs. In the first case, only vehicle-type objects are included, while person-type objects are omitted. In the second, persons are included in the CPMs according to the currently standardized inclusion rules (cf. Section III). It can be observed that the channel usage increases linearly with the MPR, independent of the type of objects included in the messages sent (note that the x-axis is not linear in Figure 3). Also, the variance of the CBR measurements is quite large, ranging from an almost entirely free channel to a fully congested channel, where the target value of the adaptive DCC of $68\,\%$ is reached. This results from the complex channel model used for the simulation since it models obstruction of radio transmissions by buildings, which are plenty in the densely built MoST scenario. For example, a vehicle in an alley is less exposed to other vehicles transmissions than a vehicle crossing a heavily used intersection. Most importantly, it can be noticed that the additional resources required to exchange CPMs with persons included are relatively small. For all MPRs, the median of the CBR increases about $14\,\%$ on average in this scenario.

While the CBR can be seen as the cost to transmit person-type objects, Figure 4 shows the benefit, i.e., the number of unique objects that vehicles receive information about. It is evident that with rising MPR, the number of known objects rises, as more vehicles can detect objects and transmit them in CPMs. Thus, the overall sensor coverage increases. Unlike the CBR, this effect does not scale linearly, but there is an observable saturation effect for all object types. This effect is mainly caused by the overlap of areas perceivable by equipped vehicles. Statistically, the additional area observable by an additional equipped vehicle that was previously unobserved gets smaller with each new vehicle. Therefore, also the number of newly detected objects grows slower when more and more vehicles are equipped.

When comparing the number of objects by their type, it can be seen that a large portion of received objects in the CPMs are persons. The cost of sending these additional objects in terms of CBR, however, is relatively low. However, this does not lead to the conclusion that vehicle-type objects are generally more expensive to transmit. This would attribute the cost of other containers in the CPM, such as the Station Data Container (SDC) and Sensor Information Container (SIC), and the overhead of the lower layer protocols towards vehicle-type objects only. Also, the different inclusion rules for both types might lead to a different amount of channel usage depending on the traffic situation. For example, a stationary vehicle will be included less often than a person, while a vehicle driving more than $4\,\mathrm{m\,s^{-1}}$ will be included more often.

Since the inclusion rules for person-type objects are primarily based on timing rather than dynamics, the update reception interval for these objects is of interest. Furthermore, the inclusion of additional objects might negatively impact the update interval for vehicle-type objects due to channel constraints or message fragmentation if too many objects need to be transmitted at once. Figure 5 shows the interval between two updates for the same object by any CPM, aggregated

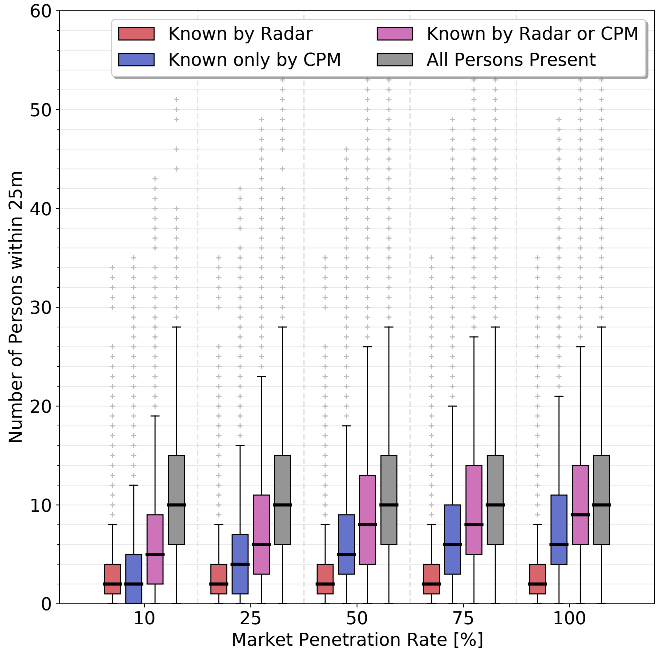

Fig. 6: Person-type objects within a range of $25\,\mathrm{m}$ to vehicles and their detection state, indicating perception capabilities of sensors and the CPS.

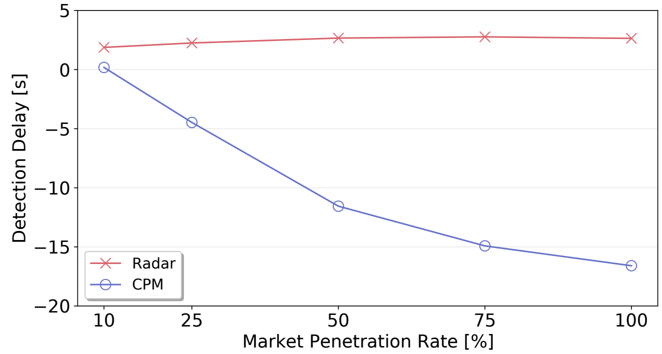

Fig. 7: Average detection delay for person-type objects, indicating the time difference between the objects entering the range of $25\,\mathrm{m}$ and their detection.

over all vehicles for each MPR. First and foremost, the interval decreases with rising MPR since more vehicles are able to perceive objects and include them in their CPMs. For persons, the increase of MPR generally improves the time between updates quite drastically, starting from $600\,\mathrm{ms}$ at $10\,\%$ MPR, reaching a median update reception interval of $130\,\mathrm{ms}$ with $100\,\%$ MPR. The update interval exceeds the specified $500\,\mathrm{ms}$ inclusion threshold regularly due to the time-triggered behavior of the simulated vehicles, checking the inclusion conditions every $100\,\mathrm{ms}$.

It can also be observed that the inclusion of person-type objects leads to a slightly increased update reception interval for vehicle-type objects, which means that messages are not successfully received. As this increase becomes more evident at higher MPRs, it can be attributed to situations where the channel is highly congested. The reason for this is twofold: firstly, higher channel congestion leads to a higher chance of message collisions and, therefore, fewer updates. Secondly, the larger messages containing more objects are less likely to be received without collisions when the channel load is high. However, the maximum increase for all MPRs amounts to $9.1\,\%$ ($24\,\mathrm{ms}$ vs. $22\,\mathrm{ms}$) and might be negligible for most applications using the object data. Additionally, when considering the benefits of having additional information about more vulnerable traffic participants available, as shown in Figure 4, this reduction might be worthwhile.

While previous metrics are more oriented towards the cost of CPS and awareness it provides for persons in general, they do not necessarily give insight into the received object's usefulness. Hence, it was analyzed how aware vehicles are of their immediate surrounding, i.e., which unique person-type objects are known. The immediate surrounding is based on a $25\,\mathrm{m}$ range threshold, defining a simplified safety-relevant area. The range is determined by the total stopping distance at a travel speed of about $13\,\mathrm{m\,s^{-1}}$ ($50\,\mathrm{km\,h^{-1}}$) for the inner city, with a braking deceleration of $7.5\,\mathrm{m\,s^{-2}}$ and a reaction time of $1\,\mathrm{s}$. It is assumed that all objects within this range should be observable for vehicles in order to detect potentially dangerous situations, such as pedestrians stepping onto the road in front of the vehicle or a bicyclist coming from behind, closing the distance while the vehicle waits at a traffic light. Figure 6 shows that half of the vehicles can only perceive between one and four person-type objects within the range of $25\,\mathrm{m}$ with their local sensors. However, $50\,\%$ of vehicles also have between 6 and 15 persons present in their vicinity, which they cannot perceive by themselves. Hence, many persons nearby are obstructed by buildings or other vehicles, and thus, have the potential to create dangerous situations. These distributions remain almost constant with rising MPR since newly equipped vehicles will statistically have the same number of persons in their surroundings as other, previously equipped vehicles. With an MPR of $10\,\%$, person-type objects received by CPM that the receiver was unaware of otherwise can improve the number of persons known by a factor of two. When increasing the MPR to $25\,\%$, vehicles already receive twice the number of additional person-type objects as they are able to detect themselves. With the further increase of the MPR, the number of known persons by CPM still rises but shows the same saturation effect seen in Figure 4. At $75\,\%$ MPR, equipped vehicles are aware of $85\,\%$ of all persons in their vicinity, receiving three times the amount of person-type objects by CPM they can perceive with their local sensors. While the awareness increases only slightly when equipping more vehicles, this shows a significant improvement compared to local perception only and that CPM can substantially raise awareness of persons, improving the information base for safety applications.

Apart from the awareness of person-type objects within the safety-relevant area, it is also crucial how soon the vehicle

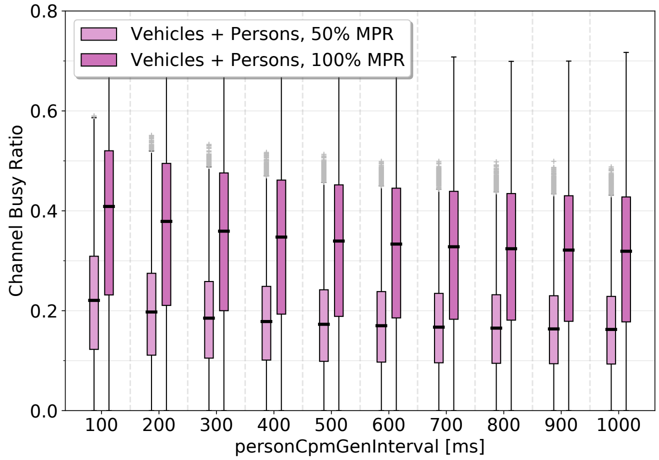

Fig. 8: Resulting CBR for different person inclusion intervals at $50\,\%$ and $100\,\%$ MPR

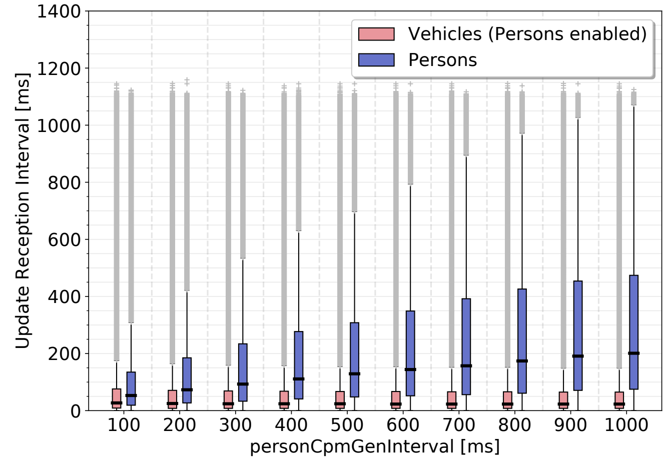

Fig. 9: Resulting update reception intervals for different person inclusion intervals at $100\,\%$ MPR

can detect an object entering the said area, such that an emergency brake is still possible. Hence, the detection delay for these objects was analyzed. Figure 7 shows how long it takes for vehicles to perceive an object, either via local sensors or via CPM, after it enters the safety-relevant area. When considering local sensors only, it takes an average of $2.5\,\mathrm{s}$ until a person entering the area is detected. Considering that vehicles drive around $13\,\mathrm{m\,s^{-1}}$ in this scenario, they can travel more than $30\,\mathrm{m}$ in that time. This shows that in some situations, e.g., pedestrian stepping on the road, the reaction time for a dangerous situation would be non-existing since the vehicle would not be able to stop in time. However, when person-type objects via CPMs are considered, it can be noticed that the average detection delay is either zero or negative, e.g., persons are known before they enter the safety-relevant area. Therefore, equipped vehicles have a larger time window for tracking, planning, and reacting as they can build a horizon much further into the future. Similar to Figure 4 and Figure 6, the detection delay shows the same saturation effects.

Since the *personCpmGenInterval* is statically specified as $500\,\mathrm{ms}$ in [1] without further explanation, it raises the question of how different intervals influence the results, and therefore, need to be investigated. Figure 8 shows the CBR aggregated over all vehicles in a simulation with given MPR for varying intervals. As expected, with a lower interval for the inclusion of person-type objects, the load on the channel increases. For the CPS to include person-type objects every $100\,\mathrm{ms}$ instead of every $500\,\mathrm{ms}$, $50\,\%$ MPR would increase the channel load by approx. $28\,\%$, while $1000\,\mathrm{ms}$ would reduce the load only by $7\,\%$. A similar effect can be seen at $100\,\%$ MPR, where the load increases by $20\,\%$ with an interval of $100\,\mathrm{ms}$ and reduces by $6\,\%$ with $1000\,\mathrm{ms}$. With the increase of the interval, both CBRs converge towards the CBRs measured for the respective MPR without person-type objects (see Figure 3), which determines a lower boundary for the CBR.

In Figure 9, the impact of different *personCpmGenIntervals* on the update reception interval is shown for an MPR of $100\,\%$. Most notably, the interval in which vehicles receive updates for person-type objects increases almost linearly when the generation interval is increased. The dynamics-based inclusion rules for vehicle-type objects, in contrast, can achieve an update reception interval of $40\,\mathrm{ms}$ on average, and their update rate is mainly unaffected by the *personCpmGenInterval*. With the standardized *personCpmGenInterval* of $500\,\mathrm{ms}$, receivers get an update about person-type objects every $130\,\mathrm{ms}$ (median). When the generation interval is reduced to $100\,\mathrm{ms}$, the update reception interval for persons can be improved by $62\,\%$ to $50\,\mathrm{ms}$, while using an additional $20\,\%$ of channel resources (cf. Figure 8). However, if the generation interval is increased to $1000\,\mathrm{ms}$, the update reception interval for persons increases by approx. $54\,\%$ to $200\,\mathrm{ms}$, but frees only $7\,\%$ of channel resources.

These results show that a highly increased update rate for person-type objects is possible with moderately increased additional resources. Increasing the *personCpmGenInterval* and, therefore, increasing the update reception interval for persons would not conserve a significant amount of channel resources. With an assumed walking speed of $5\,\mathrm{km\,h^{-1}}$ or $1.4\,\mathrm{m\,s^{-1}}$, the current specification would statistically lead to an update after $18\,\mathrm{cm}$ of movement at $100\,\%$ MPR. An increased interval of $100\,\mathrm{ms}$ would result in updates after $7\,\mathrm{cm}$, whereas $1000\,\mathrm{ms}$ would lead to updates every $28\,\mathrm{cm}$. With an MPR of $10\,\%$ and $50\,\%$, using a $500\,\mathrm{ms}$ inclusion interval, statistically, the distance between two updates would be $84\,\mathrm{cm}$ and $46\,\mathrm{cm}$, respectively (cf. Figure 5). Hence, the right choice of the *personCpmGenInterval* highly depends on the update rate required by safety applications utilizing received CPM data and the MPR, but also on the accuracy of localization measurements for person-type objects.

VI. Conclusion

The CPS will play an essential role in the early adoption phase of V2X, bridging the gap between modern, communicating, and legacy vehicles. While much work has been done in the development and standardization of collective perception, most of it was focused on vehicles. However, persons (i.e., pedestrians and bicyclists) play an important role in key use-cases of collective perception, but their inclusion rules have not gotten much attention so far.

Therefore, in this paper, we analyzed their inclusion rules currently laid out in the standard. The additional channel load induced by adding persons as perceived objects to CPMs was found to be rather limited. However, the number of known objects via CPM significantly increased, where almost half of the objects known to vehicles were person-type objects. Including persons in CPMs did not significantly impact the time between updates for vehicle-type objects. While increasing the MPR leads to a saturation effect of known objects, it significantly impacts the update reception intervals for both vehicle and person-type objects. However, it is more beneficial for persons. Furthermore, we analyzed the potential safety benefit of the CPS for persons by measuring the awareness of unique person-type objects in the direct vicinity of vehicles. It was found that even with powerful sensor equipment, vehicles were only able to perceive a small number of relevant persons, while the CPS was able to significantly increase awareness and reduce the detection delay for persons nearby. Finally, the channel utilization and the update interval depending on the inclusion interval for person-type objects were analyzed. The results show that the CPS could enable tracking of obstructed person-type objects with varying uncertainty radius between $80\,\mathrm{cm}$ and $7\,\mathrm{cm}$, depending on the inclusion interval and the MPR. Since the MPR of the CPS will evolve over time and cannot be influenced directly, the right choice for the inclusion interval of person-type objects depends on the required precision. However, the question regarding the precision for effective tracking and, therefore, applications improving safety for persons requires further research.

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