V2X-Clustering for Bicycles: An Analysis of Efficiency and Alternatives

Nico Ostendorf
Robert Bosch GmbH &
TU Braunschweig
Hildesheim, Germany
nico.ostendorf@de.bosch.com

Keno Garlichs
Robert Bosch GmbH
Hildesheim, Germany
keno.garlichs@de.bosch.com

Lars C. Wolf
TU Braunschweig
Braunschweig, Germany
wolf@ibr.cs.tu-bs.de

***Abstract*—As Vehicle-to-X (V2X) communication gains attention for protecting cyclists and other Vulnerable Road Users (VRUs), managing the resulting channel load is an important challenge. This paper evaluates the standardized clustering method for VRU Awareness Messages (VAMs) on bicycles. To assess its effectiveness, we benchmark its performance against two other approaches: the standardized Redundancy Mitigation (RM) technique, and a mechanism we term Message Frequency Reduction (MFR). This MFR approach serves as a low-complexity comparative approach, reducing the message frequency when a bicycle is at a standstill. Our evaluation, using a high-density urban simulation from Hannover, Germany, finds that while the overall Channel Busy Ratio (CBR) contribution from bicycles is moderate, situational channel load peaks can be high, showing the need for mitigation strategies. However, the results demonstrate drawbacks for the evaluated methods. The results demonstrate that the standardized clustering approach is unsuited for bicycles, as it not only failed to mitigate peak channel load but also increased the maximum CBR at full penetration rates. The comparative analysis underscores this ineffectiveness. While RM provided a slight reduction in CBR, it comes at the direct expense of bicycle perception, and the MFR approach, though the most consistent, also offered only a modest CBR reduction while introducing its own safety trade-offs. Our findings therefore indicate that the standardized clustering mechanism, in its current form, is not a viable strategy for managing V2X channel load for cyclists and could even negatively impact network performance in dense environments. This highlights the need for future work to develop novel and suitable congestion control mechanisms specifically designed for the unique characteristics of V2X-equipped cyclists.**

***Index Terms*—Vehicle-to-X, Vehicular Ad hoc Networks, Vulnerable Road User, Simulation**

I. Introduction

In recent years, road safety has become an important topic as the number of road users rises and traffic accidents are among the top reasons for deaths [1]. In 2021 alone, the World Health Organization (WHO) reported 1.19 million road fatalities and 50 million non-fatal injuries [2]. In response, authorities like the European Commission have set ambitious goals, such as the Vision Zero initiative, which aims to eliminate all road fatalities by 2050 [3].

While new technologies and regulations have led to a general decrease in fatality rates in the European Union, a comparable decrease is not observed for riders of two-wheeled vehicles, such as motorcycles and bicycles, in either the long or short term, as shown in [4]. In fact, over the long term, cyclists are the only road user group for which fatalities have actually increased [5]. This trend can be attributed to factors such as the rising number of cyclists and their lack of integration into active technical safety systems. Such an integration could be done by the standardized Vehicle-to-X (V2X) communication, which is also identified by the European Commission as a key technology for achieving Vision Zero.

V2X enables road users and roadside infrastructure to dynamically share status information like their speed, position, heading, and sensor data such as detected objects, by broadcasting different standardized messages such as the European Cooperative Awareness Messages (CAM), Collective Perception Messages (CPM), and Vulnerable Road User Awareness Messages (VAM), alongside similar message utilized in other regions. This information exchange enables various applications, such as collision warnings, cooperative lane merging, and advanced driver assistance systems, as detailed in [6]. Although V2X technology is already deployed in some vehicles, its absence on bicycles represents a safety gap.

Nevertheless, if the group of potential V2X users continues to expand to include not only vehicles, the importance of efficient communication is becoming increasingly apparent as the resources of existing V2X channels are limited. If those channels become congested and prevent the reliable exchange of information, the full safety potential of V2X cannot be realized, also hindering the achievement of goals like Vision Zero.

To address such an increasing channel load, due to the integration of other road users and new messages, various mitigation methods have already been developed. For instance, Decentralized Congestion Control (DCC) [7] aims to equitably distribute available V2X channel resources. Also strategies to reduce the number of broadcasted messages and their associated overhead before mitigation even occurs exist. One such strategy is clustering, which groups Vulnerable Road Users (VRUs), like pedestrians and bicycles, to share their information in one joint message instead of individual messages for each participant. Another approach with a similar purpose is Redundancy Mitigation (RM), which aims to suppress messages which include information very similar to what was already shared in an earlier message. While

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clustering is already a part of the VRU Awareness Message (VAM) [8], research on clustering has predominantly focused on pedestrians. The applicability and performance of this technique for cyclists, a group with fundamentally different movement dynamics, remain largely unexplored, highlighting a clear need for further investigation. This research gap is critical given the forthcoming adoption of the CAM for bicycle use, a standard that currently lacks an integrated congestion control mechanism.

This paper addresses this gap by evaluating the suitability of the standardized V2X clustering mechanism for bicycles. We conduct a comparative performance analysis, comparing clustering against the RM technique, which was analyzed on its own in our previous work [9], and a novel, low-complexity method we introduce as Message Frequency Reduction (MFR). In MFR, a bicycle reduces its message frequency based on whether it is at a standstill or moving. The performance of these strategies is quantified by their impact on the Channel Busy Ratio (CBR) to determine whether clustering is a suitable congestion control strategy for V2X-enabled bicycles, or if its performance is inferior to the RM and MFR alternatives.

To assess V2X communication performance under realistic conditions with a high volume of bicycle traffic, we used a comprehensive simulation framework. This framework integrates the SUMO (Simulation of Urban MObility) traffic simulator [10] coupled with OMNeT++ [11], and its framework INET in combination with the vehicular network simulation framework Veins [12], for accurate V2X network modeling. As a simulation scenario, we used the open-source Hannover Traffic Scenario (HaTS) [13] which includes a day of traffic of vehicles as well as bicycles based on traffic counts in Hannover, Germany. Additionally, to ensure realistic bicycle behavior, which is important for V2X communication simulations, we integrated the Realistic Bicycle Dynamics Model for SUMO [14]. This approach allowed us to accurately assess V2X communication performance in a context reflective of real-world conditions.

The remainder of this paper is structured as follows: Section II provides an overview of related work. The fundamentals of V2X for bicycles are explained in Section III. The standardized clustering approach and analyzed alternatives are explained in Section IV. The used simulation environment is explained in Section V as well as the results of the evaluations. Section VI and Section VII finalize the paper with a discussion and the conclusion.

II. Related Work

As the V2X ecosystem expands to include more participants and new message types, effective management of wireless channel congestion will be critical for ensuring network scalability and reliability in future. To address the message overhead from individual VRUs, clustering has been proposed as a primary mitigation strategy within the VAM standard. The literature explores the overall concept of clustering through both decentralized and centralized methodologies, with a predominant focus on pedestrians.

A. Decentralized and VAM-Based Clustering

Decentralized, self-organizing clustering is a part of the VAM standard. Foundational research by Lobo et al. [15] demonstrated that VAM clustering could significantly reduce the CBR from over 68% to below 20% in a high-density pedestrian scenario. In a subsequent study, they addressed the congestion caused by failed cluster-join requests by introducing an adaptive message prioritization scheme, further improving channel efficiency [16].

Similarly, Rupp et al. [17] confirmed that VAM clustering effectively reduces message volume for pedestrian groups in C-V2X systems. However, they highlighted a critical trade-off, noting that this efficiency gain resulted in an increased average position error, which could be as large as several meters.

A study that includes both pedestrians and cyclists was conducted by Lobo et al. in the Ingolstadt Traffic Scenario (InTAS) [18]. While this work provided a valuable mixed-VRU environment, its traffic composition was limited to buses, pedestrians, and cyclists, excluding the influence of general vehicular traffic on cyclist behavior. Their results showed that clustering occurred almost exclusively at high-density pedestrian locations like bus stops, and no bicycles joined a cluster throughout the entire day-long simulation. This finding raises pivotal questions about the VAM clustering standard's applicability to cyclists, especially in more realistic, mixed-traffic environments.

B. Centralized Clustering

In contrast to these decentralized methods, centralized clustering often leverages infrastructure-based sensors. Xhoxhi et al. [19] explored the trade-off between the accuracy of the cluster's shape and the resulting channel load. While complex polygons can represent pedestrian groups with high accuracy, they provide the least reduction in data transmission. Simpler geometric shapes, such as rectangles, reduce the data load more significantly but at the cost of lower accuracy. Their analysis concluded that a rectangle offers the best compromise between data reduction and positional accuracy.

Applying a similar concept in a vehicular context, Chen et al. [20] proposed a zone-based clustering strategy to improve the tracking of pedestrian groups for autonomous vehicles. This method is designed to account for the perspective distortion from vehicle-mounted cameras, offering more reliable performance.

C. Research Gap and Contribution

The existing literature establishes that VAM-based clustering is a viable congestion control strategy for pedestrians, albeit with possible trade-offs between data load and positional accuracy. However, there is a gap concerning its application to cyclists. To date, only one study has specifically included cyclists as VRUs, and it concluded that the clustering is ineffective for this user group [18]. While we concur with the

fundamental premise that the distinct movement dynamics of cyclists lead to different clustering performance, we hypothesize that the ineffectiveness reported by Lobo et al. may be less severe in higher-density, mixed-traffic scenarios that we want to investigate.

This paper directly addresses this research gap by evaluating the standardized VAM clustering mechanism for cyclists within such a high-density, mixed-traffic scenario. We analyze its performance and compare it against alternative congestion control strategies to determine its viability for this distinct group.

III. Fundamentals of V2X for Bicycles

Bicyclists are classified as Vulnerable Road Users (VRUs), a category that also includes pedestrians, motorcyclists, and animals. While the primary message type defined for VRUs is the VAM [8], the release of ETSI TS 103 900 V2.2.1 [21] now also permits bicycles to broadcast CAMs. Originally, the CAM was designed to broadcast the ego-status of a vehicle, while the VAM served the equivalent purpose for a VRU. Since the fundamental data for this, such as position, speed, and heading, is similar for both, their message structures and included information are comparable.

A. Message Structure

Both the VAM and CAM are built upon a similar container-based structure. Figure 1 shows an example of the VAM structure. The Basic Container and the High-Frequency Container are mandatory in both, as they carry essential dynamic information such as the vehicle's current position, speed, and heading.

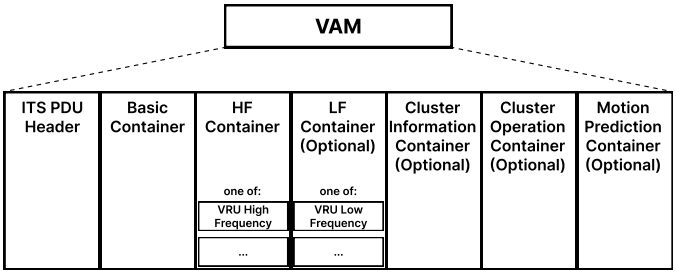


Fig. 1: General structure of a VAM based on [8].

In addition to these, both message types share optional containers that provide valuable supplementary data. For instance, the Low-Frequency Container can be used in both messages to inform about the road user type or light status. However, each message type also features its own exclusive set of optional containers. The CAM can optionally include a Special Vehicle Container (e.g., for emergency vehicles) and several extension containers, such as the Two-Wheeler Container for bicycle and motorcycle specific data or the Path Prediction Container. The VAM exclusively features the Cluster Information (CI) and Cluster Operation (CO) container, which are essential for the clustering mechanism. It also optionally includes a Motion Prediction Container to broadcast predicted trajectory information.

B. Message Generation Rules

A major difference between the two messages lies in their transmission frequency and the rules for message generation. The CAM is transmitted at a frequency between 1 and 10 Hz, while the VAM has a broader range of 0.2 to 10 Hz. The triggering conditions for a new message are also distinct. A new CAM must be transmitted if at least one second has passed since the last message or if any of the following dynamic conditions are met:

(i) A position change of $\geq 4\,m$.
(ii) A heading change of $\geq 4\,°$.
(iii) A speed change of $\geq 0.5\,m/s$.

The rules for the VAM are similar but include additional triggers. A new VAM is sent if five seconds have passed, if the dynamic thresholds above are met, or if specific events occur. These events include the VRU joining or leaving a cluster, a new participant entering a predefined safe distance, or a change in the probability of a trajectory interception.

Given that the information contained within the VAM and CAM is largely comparable, this paper aims to analyze whether a congestion control mechanism like clustering, currently exclusive to the VAM, would be a beneficial addition to the CAM standard, specifically for bicycles.

IV. Methodologies: Clustering and Alternatives

This section introduces and compares methods for reducing V2X channel load by minimizing message overhead, with a focus on their applicability to bicycles. We first explain the VRU clustering mechanism as specified for the VAM in ETSI TS 103 300-3 [8]. To provide a comparative analysis, we then introduce RM and MFR. Although clustering and RM were originally developed for the VAM, we implemented them within the CAM for our analysis because the message sizes of VAMs and CAMs are comparable, and the fundamental logic of these mitigation mechanisms affects both message types in an identical manner. Consequently, the findings from our CAM-based analysis are directly transferable to the VAM. This integration allows us to assess their effectiveness for bicycle-based communication and to determine whether they warrant adoption into the CAM standard.

A. Clustering Mechanism

The VRU clustering mechanism, specified in ETSI TS 103 300-3 [8], is a method to reduce the amount of broadcasted VAMs and decrease channel load. It allows VRUs with similar movement patterns, such as bicycles, to form a group as shown in Figure 2.

Each cluster is managed by a designated cluster leader. The leader's responsibilities include creating the cluster, managing its membership, and broadcasting the cluster's status. This is achieved by embedding a CI container within its own messages. The CI container includes essential data such as the cluster's reference position and velocity, the total number of

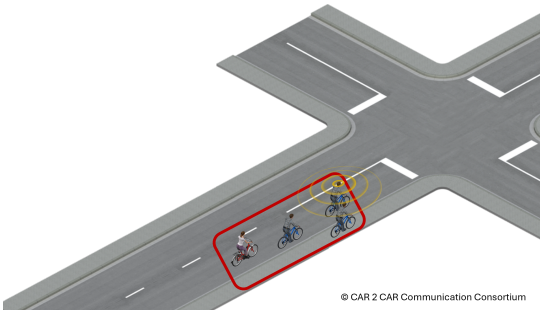


Fig. 2: Example of a Clustered Group of Bicycles.

members, and a bounding box that encompasses all members (depicted by the red area in Figure 2). To ensure efficient communication, only the cluster leader transmits messages on behalf of the group. All other members disable their own transmissions. This principle is illustrated in Figure 2, where only the leader is shown with transmission indicators (yellow circles).

The standard defines four roles. A VRU not taking part in the V2X communication is a `VRU-IDLE`. A VRU taking part in the V2X communication and is not in a cluster is a `VRU-ACTIVE-STANDALONE`. The leader of a cluster is a `VRU-ACTIVE-CLUSTER-LEADER`, and a non-leading member of a cluster is a `VRU-PASSIVE`. Figure 3 shows how VRUs change between these roles based on specific actions.

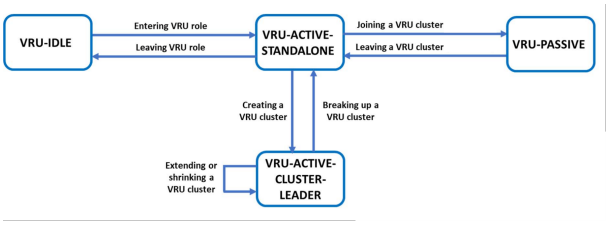


Fig. 3: VRU Roles During the Clustering Mechanism. [8]

The following actions control the clustering process:

Cluster Creation: A `VRU-ACTIVE-STANDALONE` can create a cluster if it receives VAMs from at least `numCreateCluster` $= [3-5]$ other VRUs within `maxClusterDistance` $= [3-5]\,m$. The VRU then becomes the `VRU-ACTIVE-CLUSTER-LEADER` and starts broadcasting the cluster information in its VAM.

Cluster Breakup: A leader can break up its cluster, for example, if the creation conditions are no longer met or if no one is joining its cluster. The leader must announce the breakup in its VAM for `timeClusterBreakupWarning` $= 3\,s$ before it stops sending cluster information in its VAM.

Joining a Cluster: A VRU can join a cluster if it meets the following criteria: its distance to the cluster is less than `maxClusterDistance`, the cluster has fewer than `maxClusterSize` $= 20$ members, and its velocity difference from the leader is less than `maxClusterVelocityDifference` $= 5\%$. The velocity is defined as a vector based on speed and direction. To start the join process, the VRU sends a join notification in its VAM for `timeClusterJoinNotification` $= 3\,s$. The VRU must then observe the leader's subsequent VAMs to confirm that it has been included in the cluster. Once the inclusion is verified, the VRU becomes `VRU-PASSIVE` and stops sending its own VAM.

Leaving a Cluster: A VRU must leave a cluster if it no longer meets the join criteria or if it moves outside the cluster's bounding box. A VRU also leaves if it does not receive a VAM from its leader for `timeClusterContinuity` $= 2\,s$. To leave, the VRU sends a leave notification for `timeClusterLeaveNotification` $= 1\,s$ in its own VAM and becomes a `VRU-ACTIVE-STANDALONE` again.

Cluster Extension/Shrinking: The cluster leader must extend or shrink the cluster when a member joins or leaves. The leader updates the cluster's bounding box and number of members to match the new size.

A design challenge emerges during cluster shrinking. The communication protocol is one-way. Members receive information from the leader but do not transmit their own position while in the cluster. Consequently, a member can move freely within the bounding box without the leader's knowledge, potentially making the bounding box an inaccurate representation of the members' true positions over time.

This issue emerges especially when a member leaves the cluster, as illustrated in Figure 4. Since the leader lacks real-time positional data for all members, it cannot safely shrink the bounding box. For instance, if the leaving member was originally at the edge of the cluster, shrinking the boundary to its last known relative position could also exclude other members who have moved into that space. Such an imprecise bounding box can lead to significant positioning errors, as documented in [17].

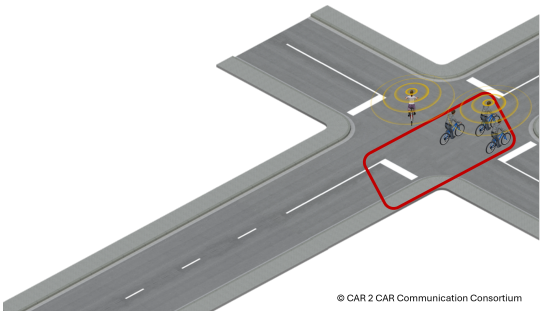


Fig. 4: Example for a Problem with Cluster Shrinking.

B. Redundancy Mitigation

One alternative mechanism to clustering is RM, which is also specified in the ETSI TS 103 300-3 [8]. The principle of RM is similar to clustering, as its objective is to minimize the transmission of redundant information. In this context, information is considered redundant if another VRU's transmitted VAM sufficiently represents the ego-VRU's own dynamic state.

The standard specifies a set of rules to govern this process. A VRU is permitted to suppress its own VAM transmission if all of the following conditions are satisfied:

(i) The time elapsed since the last ego VAM does not exceed $\texttt{numSkipVamsForRedundancyMitigation} \cdot T_{\texttt{GenVamMax}} = [2, 10] \cdot 5000\,ms$.
(ii) A recently received VAM from a reference VRU has a heading difference of less than 4°.
(iii) The absolute speed difference to the reference VRU is less than 0.5 m/s.
(iv) The distance to the reference VRU is less than 4 m.

The primary difference from clustering is that in RM, a VRU simply stops transmitting without another entity explicitly reporting its presence. This introduces a significant drawback, as the redundant VRU becomes temporarily invisible for other V2X participants. The advantage of RM, however, is that it requires no explicit message exchange, such as join or leave requests, to start or stop VAM suppression.

The standardized RM approach as defined in ETSI TS 103 300-3 [8] has certain weaknesses that can lead to non-redundant VRUs incorrectly suppressing their VAMs. To address this, we implemented an improved RM mechanism, which is detailed in our previous work [9]. The primary difference is in the timing of the redundancy validation. In the standardized implementation, received VAMs are cached in a local dynamic map, and the redundancy check is performed only when the ego-VRU is about to generate its own VAM. This can result in comparisons against potentially outdated information. In contrast, our developed approach performs this validation check immediately upon the reception of a VAM, ensuring the comparison is always made against the most recent data.

C. Message Frequency Reduction

As a low-complexity method for the comparison of overhead reduction, we implemented an approach that uses the principle of decreasing the transmission frequency of a bicycle in certain situations. We termed it MFR. A simple, unconditional reduction in all situations would negatively impact a bicyclist's visibility and compromise safety. Therefore, our developed approach applies a conditional frequency reduction only in situations where the safety impact is minimal but the potential channel load benefit is high.

Specifically, our mechanism proposes that bicycles which have reported themselves as stationary in a broadcasted message should reduce their transmission rate. Since our later evaluation is based on the transmission of CAMs, the minimum frequency is set to 1 Hz. MFR reduces this rate for stationary bicycles to one message every five seconds (0.2 Hz), which represents a significant reduction. This lower frequency remains compliant with the VAM standard, wherein a 0.2 Hz rate is already prescribed for bicycles at a standstill. For surrounding vehicles, the implication is that upon receiving a message from a stationary bicycle, they can assume it will remain at that position for the subsequent five seconds unless a new message is received. This results in a fivefold reduction in message transmissions for every stationary bicycle. However, this approach introduces a potential drawback. If a vehicle fails to receive a broadcasted message due to signal obstruction (e.g., from a building), the stationary bicycle could remain invisible to that vehicle for up to five seconds, even if it is very close to the vehicle.

A key advantage of this mechanism is that it operates independently of other V2X users. Consequently, the approach should be effective even at very low V2X market penetration rates for bicycles, which could be different for the other approaches.

V. Evaluation

This section evaluates the effectiveness of the proposed clustering method against the alternative approaches using an extensive simulation study. A simulation-based approach was adopted due to the lack of real-world data encompassing high-density scenarios of multiple bicycles with the dynamic data required for V2X message generation. The subsequent subsections detail the simulation environment, scenario design, parameter variations, and a comprehensive analysis of the results.

A. Simulation Environment

Table I details the important simulation parameters employed in this study.

TABLE I: Simulation Parameters

Parameter	Value
Protocol Stack	ITS-G5
Frequency Band	5.9 GHz
Bitrate	6 Mbps
Obstacle Loss	Dielectric Obstacle Loss
Transmission Power	23 dBm
Scenario	HaTS [13]
Seed Amount	4
Simulation Start Time	8:30 AM
Simulation Period	30 s (incl. 10 s of warmup)

All simulations have been performed on an ITS-G5-based V2X network. To realize this network, we used the discrete event simulator OMNeT++ [11] with its framework INET in combination with the vehicular network simulation framework Veins [12]. To accurately model node mobility, OMNeT++ was coupled with the microscopic traffic simulator SUMO [10].

Given that these frameworks do not natively support the CAM and the introduced mechanisms, a new message type with CAM triggering conditions has been implemented according to the specifications [8], [21]. The size of the message is variable and based on the data included in the different messages.

To enhance the realism of bicycle dynamics, we integrated the open-source Realistic Bicycle Dynamics Model[1] [14] into SUMO. Unlike SUMO's default models, which treat bicycles either as fast pedestrians or as slow vehicles, this model enables the simulation of realistic longitudinal bicycle behavior

[1] https://github.com/boschresearch/RealisticBicycleDynamicsModel

crucial for V2X message generation rules. As simulation scenario, we selected the open-source Hanover Traffic Scenario (HaTS)[2] [13], which is well-suited for this study due to its realistic and high-density representation of bicycle and vehicle traffic.

The scenario was divided into five Regions of Interest (ROIs) for evaluation. These ROIs were primarily selected based on their high bicycle density and the presence of intersections. Additionally, the availability of traffic count data for these specific locations ensures that these regions of the scenario accurately reflect observed traffic patterns. Figure 5 illustrates the ROIs, marked as red squares. Furthermore, to include areas with lower cyclist densities, the evaluation also encompassed the full scenario.

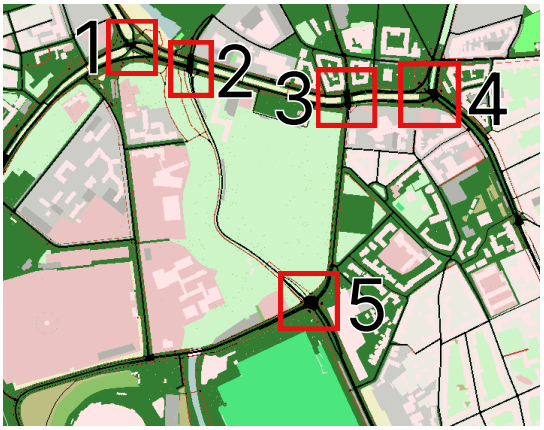


Fig. 5: Regions of Interest in HaTS.

The simulation start time was set to 8:30 AM, corresponding to the peak traffic period in HaTS. The traffic amount of the scenario over the time is shown in Figure 6. Each simulation run spanned 30 s, including a 10 s warm-up period to mitigate the impact of initial conditions and more accurately reflect real-world V2X participation initiation.

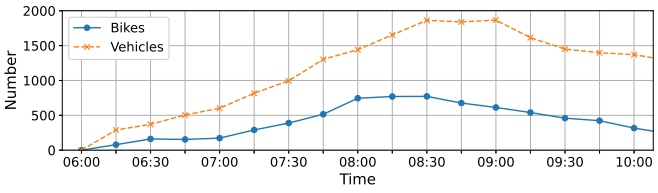


Fig. 6: Number of Vehicles and Bicycles During the Scenario.

To ensure the statistical robustness of the results and mitigate the influence of specific initial conditions, each configuration was simulated by four distinct random seeds. This approach enhances the reliability and generalizability of the findings.

It is important to note that during the simulations, only bicycles were equipped with V2X. This was done to better isolate and evaluate the impact of bicycles on the CBR and the improvements offered by the different mitigation approaches. Nevertheless, vehicles moved through the scenario to create realistic traffic flow. Based on the standards, they are not participating in the clustering or RM logic, as these approaches are designed to operate exclusively among VRUs.

For the evaluation of the channel load, we used the Channel Busy Ratio as defined in ETSI EN 302 571 [22]. CBR is calculated as the ratio of the time the channel is sensed as busy (t_{busy}) to the total measurement period (t_{CBR}):

$$CBR = \frac{t_{busy}}{t_{CBR}}.$$

For our evaluation, the measurement period, t_{CBR}, was set to 100 ms.

B. Results

The results of the CBR evaluation for the complete scenario are plotted in Figure 7 as boxplots. The median is shown by the black line. The upper and lower whiskers of the boxplots are calculated as 1.5 times the interquartile range (IQR), with the maximum or minimum value being chosen if it is smaller than 1.5 times IQR. We compared the results of different approaches: the Baseline, which is without any of the mentioned approaches, clustering, MFR, and RM. All approaches were compared at different market penetration rates: 0.1, 0.2, 0.3, 0.5, and 1.0.

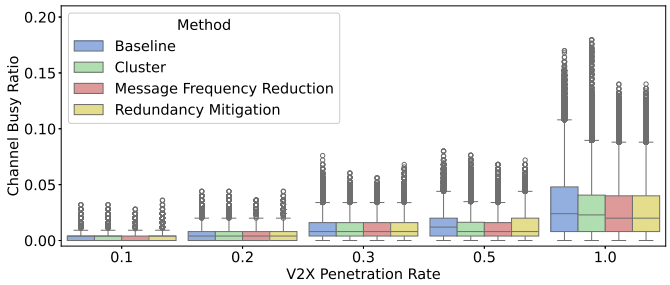


Fig. 7: Channel Busy Ratio for Different Methods at the Overall Scenario.

An initial observation is that the overall CBR produced by bicycles is not very high, even at a full penetration rate for the baseline. This is not a phenomenon specific to the chosen simulation scenario but rather a representative finding. As mentioned before, the analysis is based on a traffic scenario in Hanover, Germany, a location specifically selected for its high density of bicycle traffic. Hanover ranks as one of the cities with the largest proportion of bicycles in the modal split among German cities with 500,000 or more inhabitants, which suggests the results are applicable to other large cities [23]. While the CBR contribution from bicycles alone appears not critical, it is important to note that this additional load could become a factor in a broader V2X context, where vehicles and infrastructure also compete for channel resources, leading to a much more demanding environment.

[2]https://github.com/boschresearch/HanoverTrafficScenario

In the overall scenario, the effectiveness of the evaluated methods is highly dependent on the V2X market penetration rate. At a full penetration rate of 1.0, all approaches slightly improve the median CBR compared to the baseline. The MFR and RM methods have the most impact, each reducing the already low median by 0.4 percentage points. However, a difference is observed in the maximum CBR. The clustering approach increases the maximum CBR compared to the baseline. This is explainable by the necessary cluster operation messages, especially during cluster breakups. For instance, when a cluster of bicycles accelerates from a red light, the varying speeds cause members to leave the cluster and begin transmitting their own messages nearly simultaneously, leading to a spike in channel load. In contrast, MFR and RM significantly decrease the maximum CBR by 2.99 percentage points.

As the penetration rate decreases, the performance of the methods diverges. At a rate of 0.5, all methods reduce both median and maximum CBR, with MFR again showing the highest impact on the maximum CBR with a 15% reduction, followed by RM (5%) and clustering (4.6%). The improvement of the median CBR is similar for all cases with a 33.3% reduction. At the lower penetration rates of 0.3, 0.2, and 0.1, none of the methods could reduce the median CBR, which is attributable to an already low baseline median of below 1%. However, MFR continues to provide an improvement in maximum CBR, whereas the impact of clustering and RM becomes negligible. This is because both methods require a certain density of V2X equipped bicycles to find suitable candidates for message suppression, a condition not met at very low penetration rates. Overall, the MFR method was observed to be the most effective and robust approach for the overall scenario, delivering the best performance across all tested penetration rates.

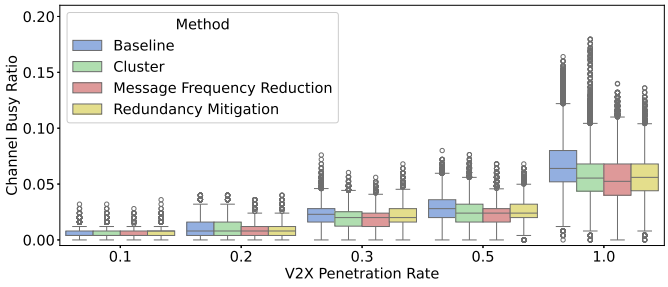


Fig. 8: Channel Busy Ratio for Different Methods at Crossing 1 in the Scenario.

Given that the previous results could be influenced by low bicycle density in parts of the scenario, the analysis was repeated for the ROIs with a high concentration of bicycles (cf. Figure 5). Figure 8 shows the results at Crossing 1. Compared to the overall scenario, the baseline CBR is significantly higher at this crossing, which is an expected consequence of the higher bicycle density. At a penetration rate of 1.0, the relative performance of the methods is similar to the overall scenario. All approaches reduce the median CBR, with MFR having the highest impact, followed by clustering and RM. Again, an increase in maximum CBR is observed for clustering, while MFR and RM are able to reduce the maximum value.

A key difference between the overall scenario and the high-density crossing emerges at the 0.3 and 0.2 penetration rates. While in the overall scenario evaluation there was no impact on the median CBR or IQR, a decrease is observable at the high-density crossing. This is attributable to the higher concentration of bicycles, where even a moderate penetration rate leads to a sufficient number of V2X equipped bicycles for the mitigation methods to become effective. Specifically, at a penetration rate of 0.3, all three methods achieve a reduction in median CBR. At the 0.2 rate, both MFR and RM decrease the IQR. Despite these effects, the MFR approach consistently demonstrates the highest overall impact on CBR reduction.

At the lowest penetration rate of 0.1, results are similar to the overall scenario: no method impacts the median, and MFR is the only one to provide a decrease in the maximum CBR.

Figure 9 shows the results for Crossing 3, which are highly consistent with the results from Crossing 1. At this location, MFR again demonstrates the highest impact on CBR across all penetration rates. As the other evaluated ROIs presented in Figure 5 showed consistent trends, we do not show these additional results explicitly in this paper.

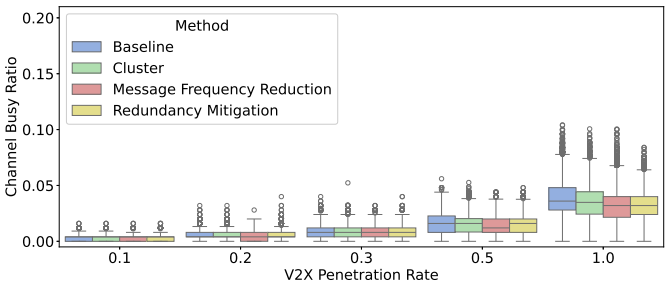


Fig. 9: Channel Busy Ratio for Different Methods at Crossing 3 in the Scenario.

In summary, the results show that the median CBR caused by bicycles is low overall, even with full penetration in a scenario with a high bicycle density, while in peak situations higher CBR values can be reached. Especially in those peaks, the clustering approach failed to reduce the channel load and, in some cases, even led to an increase in the maximum CBR due to additional operational messages. The RM method showed that it is able to provide benefits, but its performance is highly dependent on the density of other equipped VRUs, limiting its effectiveness at lower penetration rates. Of the evaluated methods, the low-complexity MFR approach proved to be the most robust, consistently providing a reliable, albeit modest, CBR reduction across all evaluated scenarios. It proved useful for CBR reduction in both high-density urban crossings and in scenarios with lower V2X penetration rates where other methods faltered.

VI. Discussion

The evaluation of the different mitigation approaches must be contextualized by a primary finding from the results section. The median CBR caused by bicycles is low overall, even with full penetration. While higher CBR values can be reached in peak situations, the low impact of bicycles questions the necessity for mitigation strategies that compromise safety. Therefore, the goal of any such strategy should be to decrease these peaks without compromising safety, yet the performance of the evaluated algorithms in this regard is questionable.

The standardized clustering approach, for instance, can be considered to have failed in its task to reduce channel load. Its impact on the median CBR was negligible, and critically, it increased the problem of channel load peaks by increasing the maximum CBR at high penetration rates. Given this, an in-depth validation of its safety impacts becomes almost unnecessary, as it already failed in its main task. Nevertheless, we also want to mention its safety implications. As shown in Section IV-A, the bounding box used to represent a cluster can become excessively large and does not shrink when members leave, which could lead to an increased position error. Such an imprecision can lead to false warnings about road users long after bicycles have passed and this can lead to potential Advanced Driver Assistance Systems (ADAS) being switched off or ignored by the driver.

The RM approach also showed only a slight impact on reducing CBR, while also having considerable safety implications. As demonstrated in our previous work [9], this approach reduces the number of detected V2X equipped bicycles by a median of 8.6 percentage points over the complete scenario. A receiving road user has no reliable way to infer the presence of a silent bicycle that has suppressed its message, creating a scenario where a V2X-equipped bicycle is effectively invisible. This presents a poor trade-off between a small channel load reduction and a potentially critical loss of awareness.

Of the evaluated methods, the low-complexity MFR was able to reduce the CBR in a stable manner, and its behavior is arguably the most predictable of the available approaches. A bicycle only stops transmitting when it is stationary and has already announced this state in a prior message. It then remains silent for a fixed interval of 5 seconds, unless it starts moving again. This allows other road users to make a relatively reliable assumption. A bicycle that has reported a standstill will remain at its last known position for the next 5 seconds or will broadcast a new message. This contrasts sharply with RM, where a road user would have to guess whether an unseen bicycle exists near a transmitting one. Suppressing messages from stationary bicycles could also be assumed to be less critical than suppressing them from moving ones, a situation possible with both RM and clustering. This is because many standstill situations occur in predictable locations, such as waiting in front of a red traffic light or on a dedicated bicycle lane. In these situations, an approaching driver is often already required to slow down due to the traffic situation itself, making the continuous V2X broadcast of the bicycle's presence less important. However, this assumption is not always true. A bicycle could be stationary in an unexpected location, for example after a fall, where the absence of continuous information could have a severe safety impact.

In summary, despite its predictability, the effectiveness of MFR is not without safety drawbacks. While it was the only approach with an impact on channel load at lower penetration rates, this can be considered a drawback rather than a benefit. In such scenarios, channel congestion is not a concern, because the CBR is already very low. To reduce safety by suppressing messages in these cases, where it is not necessary, has no advantages. Furthermore, the core safety implication of MFR remains. If a road user does not receive the single standstill message, perhaps due to signal obstruction, they would be completely unaware of the stationary bicycle for the entire 5-second interval. For a vehicle traveling at 50 km/h (approx. 14 m/s), this is a critical time frame. If it misses the standstill message from a distance of less than 70 meters, it may not receive the next update until it has already reached the bicycle's position, making braking based on V2X impossible. Additionally, even for MFR, the absolute impact on CBR is still not very high and may not present a sufficient opportunity to justify its adoption without carefully considering these drawbacks.

A. Limitations of this work

A potential limitation of this work is that the evaluation is based on a single traffic scenario. This was dictated by the limited availability of open-source SUMO scenarios that feature a high density of bicycle traffic, which was a prerequisite for this study. However, to enhance the generalizability of our findings, we did not confine our analysis to the overall scenario alone. We also evaluated several distinct ROIs within the simulation which featured different topologies. Our results showed that the behavior of the evaluated mechanisms was consistent across all tested regions. Therefore, we expect that the relative performance and the identified drawbacks of the approaches would be similar in other urban scenarios. Nevertheless, it must be acknowledged that, while Hannover is already a city with a high volume of bicycle traffic compared to other cities as mentioned before, the absolute CBR impact of bicycles could be higher in cities with an even greater bicycle presence.

A second limitation is that this evaluation is based on simulations rather than on real-world bicycle traces. While the simulation employs a model explicitly designed to reproduce bicycle behavior, real-world behavior includes a higher degree of unpredictability, such as cyclists ignoring red lights or other unexpected maneuvers, which could influence the mechanisms' performance. The use of simulation was necessary due to the lack of available datasets containing simultaneous traces of multiple bicycles in a high-density urban environment. Such data is a prerequisite for evaluating interactive mechanisms like clustering and RM, which require information from other nearby VRUs. Furthermore, the simulation represents a more idealized environment. The failure of a mechanism like clustering in this context, with its more predictable cyclist behavior,

strongly suggests that its performance would likely be even worse in a more complex, dynamic, and less predictable real-world scenario.

VII. Conclusion

This study analyzed the suitability of standardized congestion control mechanisms for V2X-equipped bicycles, comparing clustering and RM against a novel, low-complexity MFR mechanism. A primary finding is that while the overall channel load contribution from bicycles is modest, there are certainly situations in which peaks in the CBR can occur, showing the need for investigations into congestion control approaches.

Our findings indicate that the decentralized clustering approach, as currently standardized, is unsuitable for bicycle V2X applications. At a full penetration rate, clustering proved to be counterproductive by introducing higher channel load peaks due to message bursts during cluster operations, such as when a cluster disbands. Therefore, clustering fails to control peak channel load, which is a primary goal of congestion control mechanisms. Furthermore, as shown in the discussion, clustering introduces safety ambiguities through imprecise and overly large bounding boxes, which can lead to unreliable warnings for other road users.

The comparative analysis revealed that the other approaches also present significant drawbacks while having a low impact on CBR. The standardized RM approach offers only a slight CBR reduction while introducing a severe safety risk by making bicycles invisible to the V2X system. The MFR approach, while the most consistent of the three, still only provides a modest absolute reduction in CBR. Its CBR impact at low penetration rates is a questionable trade-off, reducing safety in scenarios where congestion is not a concern. Furthermore, MFR introduces additional drawbacks.

In conclusion, while clustering may be functional for pedestrians, this study has demonstrated its unsuitability and questionable necessity for bicycles. Therefore, its adoption for use in the CAM for this vehicle type is strongly discouraged. Should a congestion control mechanism still be necessary for bicycles, future research is necessary. A more promising direction for improving channel efficiency involves approaches that do not depend explicitly on other communicating partners, such as the MFR. This method has shown its ability to reduce CBR peaks. Nevertheless, such a mechanism should be adaptive and take into account the current CBR to not suppress messages and decrease safety in situations where it is not necessary. Future research should therefore focus not on adapting the existing mechanisms, but on developing novel, adaptive solutions that can provide a meaningful CBR reduction without the severe safety compromises for bicycles.

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