

## RESEARCH ARTICLE

# Cooperative Awareness Messages' Generation Frequencies, Trigger Distributions, and Pseudonym Changes of First Commercially Deployed Vehicles in Real Operating Scenarios

MAXIMILIAN BAUDER<sup>1</sup>, TIBOR KUBJATKO<sup>2</sup>,  
AND HANS-GEORG SCHWEIGER<sup>1</sup>, (Member, IEEE)

<sup>1</sup>CARISSMA Institute of Electric, Connected and Secure Mobility, Technische Hochschule Ingolstadt, 85049 Ingolstadt, Germany

<sup>2</sup>Institute of Forensic Research and Education, University of Žilina, 010 26 Žilina, Slovakia

Corresponding author: Maximilian Bauder (Maximilian.Bauder@thi.de)

This work was supported by the Bundesministerium für Bildung und Forschung (BMBF) Fachhochschule (FH)-Impuls 2020 SAFIR AVENUE under Grant 13FH71051A.

**ABSTRACT** Cooperative Intelligent Transport Systems have been deployed in mass-produced vehicles in Europe (Golf 8, ID.3, etc.) since 2019, promising major improvements in vehicle safety, efficiency, and comfort. Equipped with Vehicle-to-X communication, the vehicles directly send information about their driving status to the environment. The data are already used for many Vehicle-to-X communication use-cases specified by the Car-2-Car Communication Consortium to achieve the above-mentioned improvements. This study focuses on using Vehicle-2-X communication and its messages for accident analysis. For this purpose, we investigated the advantage in temporal resolution of the continuously sent Cooperative Awareness Message compared to the Event-Data-Recorder for accident reconstruction in the pre-crash. A high resolution of the temporal accident scene is essential for the doubtless clarification of accidents. Therefore, we analyzed the generation frequencies and the trigger conditions of the Cooperative Awareness Message of vehicles available on the European market while driving in real traffic and during different parking maneuvers. Also, the pseudonym change was analyzed. We found that the average generation frequency of the Cooperative Awareness Message is higher than the 2.00 Hz recording frequency of the event data recorder for all scenarios investigated. Especially on rural roads and highways, the temporal resolution is advantageous. Since many serious accidents occur on rural roads, the use of Cooperative Awareness Messages could significantly benefit the reconstruction of the accident scene. Thus, we recommend increasing efforts to use the Cooperative Awareness Message as digital data for accident analysis and encourage more scientists to deal with this topic.

**INDEX TERMS** Accident analysis, accident reconstruction, cooperative awareness message, cooperative intelligent transport systems, fundamental data, real operating investigation, vehicle-2-X communication.

## I. INTRODUCTION

Cooperative Intelligent Transport Systems (C-ITS) are in commercial mass production in Europe since 2019 [1]. C-ITS represent means of transport with systems for direct communication with their environment [2]. Communication with

the environment (V2X) is divided into pure vehicle communication (V2V), communication with infrastructure (V2I), or with people (V2P) [2], [3]. The cooperative vehicles currently distributed by Volkswagen in Europe use two services standardized by the European Telecommunications Standards Institute (ETSI) [4]. The Cooperative Awareness Service (CA) and its message (CAM) [5] is the subject of this study.

The associate editor coordinating the review of this manuscript and approving it for publication was Amin Mahmoudi<sup>1</sup>.

The potential benefit of using the CAM for accident reconstruction has already been proposed in [6]. The CAM could provide information about the vehicle's position, speed, orientation, longitudinal acceleration, etc., with a maximum sending frequency of up to 10.0 Hz if involved in an accident [6]. This data would be beneficial in reconstructing the accident scene, as classic connecting facts such as skid marks are diminishing due to increasing vehicle automation.

Consequently, additional digital data for the clarification of accidents is provided today by an event data recorder (EDR), which has been mandatory in every newly registered vehicle model since mid-2022 in accordance with UN-ECE R160 [7]. In the event of an accident, the EDR stores accident-relevant data up to five seconds before the crash [7]. According to [7], the parameters indicated speed, engine throttle, service brake, engine rpm, ABS activity, stability control, and steering input are saved at 2.00 Hz in the pre-crash phase.

It is apparent that the storage frequency and stored parameters contribute only a little to the reconstruction of the accident pre-crash phase. Parameters such as the position and orientation of the vehicle or current accelerations are missing. Here, the CAM could assist by providing further relevant data to accident reconstruction, especially the previously mentioned ones. In addition, the CAMs' frequencies of up to 10.0 Hz could offer five times the resolution of the EDR [5].

The variable generation frequency of the CAM, ranging from 1.00 to 10.0 Hz, prompts inquiry into the attainable frequencies of cooperative vehicles in the field under realistic operating conditions and whether this affords better temporal resolution of the accident scene as compared to the EDR.

Therefore, this study aims to analyze the generation frequencies occurring during a real road drive and parking maneuvers. The locations (urban, rural, highway) are considered separately to differentiate the occurring generation frequencies locally for the real road drive. In addition, it was found in [6] that the pseudonym change could be problematic in exploiting the CAM as digital data. Accordingly, the pseudonym change during real-road driving is also investigated.

The reason for studying parking maneuvers is the large occurring number of accidents and the associated high repair costs. From 2.31 million traffic accidents recorded by the police in Germany in 2021, 1.45 million were accidents in urban areas with property damage only [8]. According to a press release from the German insurer Allianz AG, almost half of these are related to parking accidents [9]. Consequently, it can be reasonably assumed that parking collisions are a frequent reason for accident analysis reports and cause many property damage costs in road accidents. Thus, the CAM could also be a useful digital data source in the event of a parking accident, explaining the investigation into the generation frequency of the CAM during common parking maneuvers (backwards, forwards, sideways).

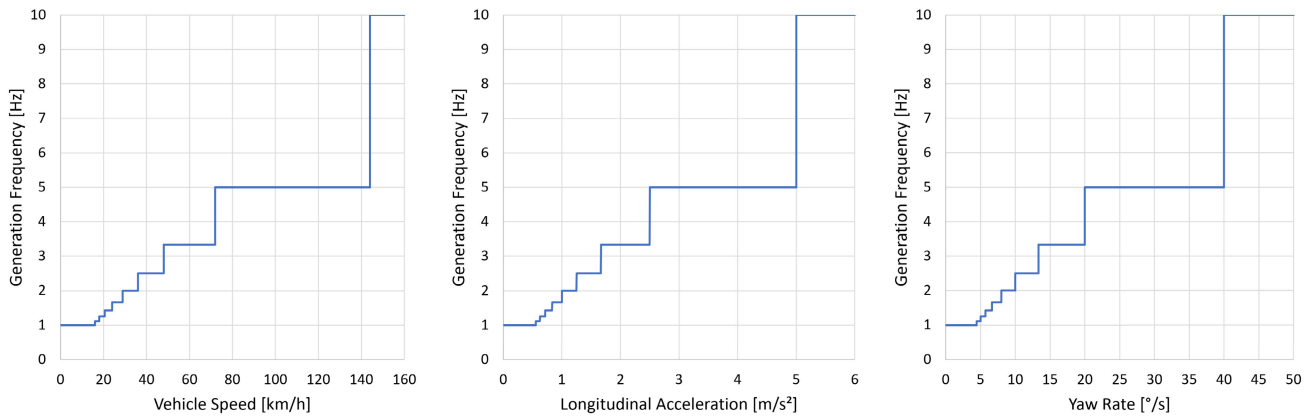
In addition to the generation frequencies, the trigger conditions that caused the CAM dissemination were analyzed for all tests. This analysis allows conclusions about the triggers that are decisive for the resulting generation frequencies in the various investigated operating scenarios. The identification and analysis of relevant triggers enable a generalization and applicability of the results while also facilitating the identification and discussion of possible influencing factors, such as the driver, vehicle, and environment.

The driving and parking tests were conducted on a test site and public roads in the Ingolstadt region with already deployed vehicles using V2X technology. At the time of the study, three Volkswagen vehicles (Golf 8, ID.3, and ID.4) equipped with V2X technology were available on the European market and used for the tests.

A related study was found by the Car 2 Car Communication Consortium (C2C-CC) in 2018, as the CAM was statistically investigated there [10]. Test drives from two vehicle manufacturers (Volkswagen and Renault) with their respective C-ITS implementations were compared. Here, the focus was mainly on the distribution of the actual data size of the CAM and the time interval between two messages (inverse of the generation frequency). Similar to this study, the vehicles were examined in real road traffic in urban and suburban areas as well as on a highway. But, compared to this study, no larger rural road sections were included. The time interval analysis of this study shows that messages were always generated in 100 ms intervals by checking the trigger conditions every 100 ms. The time interval is also very erratic from message to message. Only 50% of the messages follow in the same time interval as the previous message. The average time interval between two messages was found between 0.33 and 0.47 s and is generally very dependent on the respective driving scenario.

In another study [11], CAM messages were collected on a real-road drive, and the speed and acceleration information was evaluated. The aim was to detect changes in speed and braking events without additional sensors. It turns out that speed changes can be detected well with the help of the CAM message. Detecting braking events via acceleration information is more difficult due to the noise. However, no generation frequencies were investigated in this work.

In the study from Charpentier et al., published in [12] and [13], the authors investigated the impact of CAM size on latency, comparing the two competing transmission technologies WLANp and Cellular-V2X (C-V2X). Real-world tests were conducted on their test site in Antwerp. The result showed that the size of the message has hardly any influence on the latency. However, it became apparent that the latency of the C-V2X communication does not meet the acceptable latency requirements for pre-crash use cases. On the other hand, this study investigated no other parameters besides latency. Furthermore, no V2X-capable vehicles on the market were investigated.



**FIGURE 1.** Plotting of the resulting generation frequencies over the trigger conditions, considering the verification of the triggers in 0.1 s time intervals according to [5].

In [14], the accuracy of CAM message content was systematically investigated based on trigger conditions and compared with the accuracy requirements of V2X use cases, applications, and accident analysis. Thus, full acceleration, deceleration, constant straight-ahead, and curve driving tests were conducted. Besides the accuracy of the information sent, the generation frequencies occurring in the tests were also investigated. It was found that high generation frequencies of 5.00 or 10.0 Hz are mainly achieved at strong deceleration and acceleration. The vehicle's ground speed determines the generation frequency in constant straight-ahead driving. In the cornering tests, on the other hand, there is a high variance in generation frequencies of 5.00 Hz or less. Based on these findings, it is already possible to conclude generation frequencies for different vehicle dynamic states. However, these tests represent the generation frequency during a few individual maneuvers. An investigation of the generation frequencies occurring in real traffic and during real driving was not done.

Many other studies deal with system performance concerning CAM messages and the difference between the two competing technologies (WLANp vs. C-V2X) [15], [16], [17], [18]. As this is not the focus of this work, they are mentioned here but not discussed further.

Also, no studies on the actual implementation of pseudonym change from V2X vehicles on the market could be found. In [19], a performance evaluation of the reload of entire pseudonym lists between the vehicle and a Public Key Infrastructure was examined. The actual pseudonym change while using the pseudonyms was not considered there.

The related works show that several studies have already dealt with the CAM message. In particular, the C2C-CC study involving Volkswagen had a similar focus to this study. As the aforementioned testing was conducted before Volkswagen's initial C-ITS deployment, it would be intriguing to observe if the current market vehicles exhibit similar behavior to the 2018 tests. This has not been studied before and is a novelty

in the literature. In addition, the pseudonym changes and the generation frequency on rural roads and during parking maneuvers, have not been investigated at all yet. This is another novelty in the literature.

## II. THEORETICAL BACKGROUND, EXPERIMENTAL AND METHODS

### A. TRIGGER CONDITIONS OF COOPERATIVE AWARENESS MESSAGE

According to [5], a CAM message is generated and sent as soon as the vehicle experiences a change in heading of  $4^\circ$ , distance of 4 m, or speed of 0.5 m/s. The trigger conditions are checked every 100 ms. In addition, a CAM is sent 1000 ms after the last message if no other trigger has been true. According to the trigger conditions, a speed of 40 m/s ( $\sim 144$  km/h), an acceleration of 5 m/s or a yaw rate of  $40^\circ/\text{s}$  are necessary to achieve a generation frequency of 10.0 Hz. The resulting generation frequencies of the triggers over their respective trigger conditions are shown in figure 1.

### B. EXPERIMENTAL

The test drives in this investigation were conducted during the tests on the accuracy of the CAM message content, which was already presented before [14]. The description of the detailed experimental set-up as well as further relevant data (e.g. software status of the vehicles), can be found in this publication. Only a brief description of the experimental set-up is given here for general understanding.

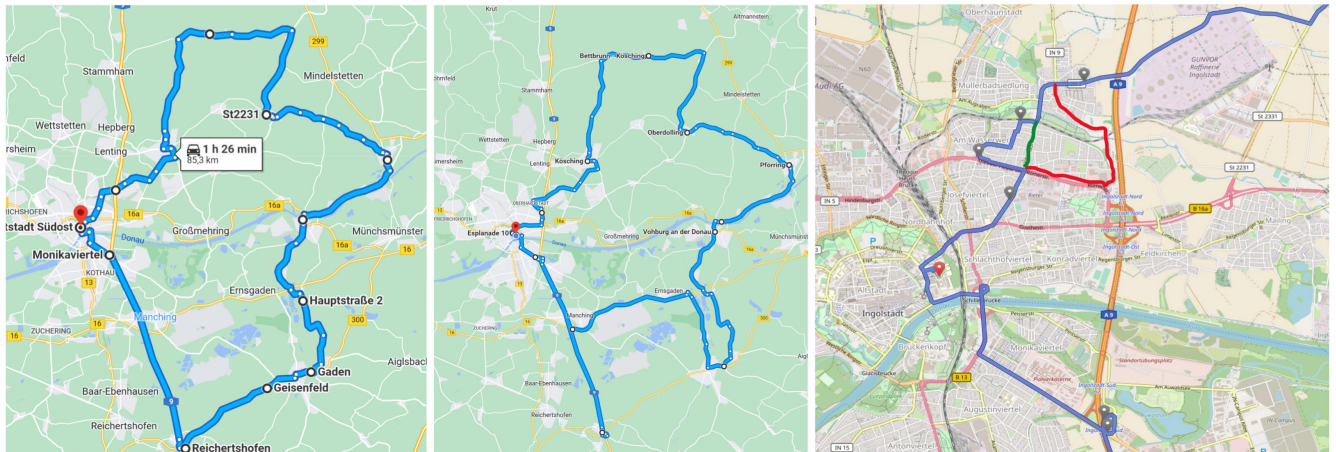
#### 1) TEST VEHICLES DESCRIPTION

All V2X-capable vehicles that were already available on the market at the time of the experiments were examined. Since Volkswagen only uses V2X technology in Europe, the Golf 8, ID.3, and ID.4 models were used for the tests. The vehicles were equipped with a V2X communication module

a) VW ID.4

b): VW ID.3 and Golf 8

c): Different driving route ING



**FIGURE 2.** a) Route driven with VW ID.4; b) Route driven with VW ID.3 and VW Golf 8; c) Change of route due to road works (green = VW ID.4, red = VW ID.3 and purple = VW Golf 8) in Ingolstadt (ING).

from the company Commsignia [20], which received the vehicle’s CAM and forwarded it to a measurement computer via Ethernet. The Data were stored together with reference data using the software ROS (Robot Operating System). The reference data are not required for this work. Thus, the reference measurement system is not described further.

2) TESTING AREAS

The measurements were realized on the test site of the CARISSMA and while driving in real traffic. The distances traveled in traffic can be seen in figure 2.

The test drive began and ended at the Technische Hochschule Ingolstadt in Ingolstadt. After the start, the city of Ingolstadt was left via the district of Oberhaunstadt in the direction of Kösching. From here, a loop was driven via Bettbrunn, Oberdolling, Pförring, Vohburg, Geisenfeld, Reichertshofen, and back to Ingolstadt. Due to road works, there were minor and major deviations from the route. For example, three different ways had to be chosen when passing through Oberhaunstadt (see figure 2 c: purple, green, and red). In addition, the road between Geisenfeld and Reichertshofen was also closed due to road works. Thus, ID.3 and Golf 8 took a route via Manching (see figure 2 b). The route selection aimed to cover all available route types (urban, rural, and highway). The route was driven with each vehicle between 10 and 12 o’clock in the morning. The test route of the VW ID.4, according to figure 2 a, is 85.3 km in total. 21.6 km were driven in urban areas, 50.2 km in rural areas and 13.5 km on highway A9. The test distance of the other two test vehicles, according to figure 2 b, is 101.1 km for the ID.3 and 100.4 km for the Golf 8. 23.3 km were driven in urban areas, 57.6 km in rural areas and 20.2 km on highway A9. Since the driven areas are considered separately, the different lengths of the routes and the changes due to the road works are not relevant to the results.

C. EXPERIMENTAL DESIGN

1) REAL-ROAD TEST DRIVE

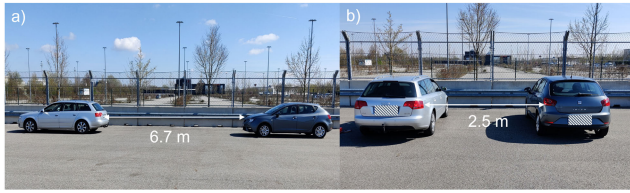
The aim of driving in a natural environment is to determine the frequencies occurring during the “normal operation” of the vehicle. This way, statements can be made about the actual CAM generation frequencies occurring in road traffic. In addition, the generation frequencies are differentiated locally, and findings on generation frequencies in urban and rural areas and highways can be generated. Furthermore, the change of used pseudonyms is evaluated. In this context, it is of interest which space and time reference the pseudonym change has. According to figure 2, the test drive was carried out once for each vehicle since, due to the long distance, enough measurement data could be collected with one run.

2) PARKING MANEUVER

The typical parking maneuvers (forwards, backwards, and sideways) were performed during the parking tests. Each parking maneuver was conducted three times by each vehicle. The parking spaces were realized by two additional vehicles (see figure 3 a) and b)) to create a parking scenario as authentic as possible. The distances between the vehicles were chosen according to the recommendations for parking facilities in Germany [21], [22]. The tests aim to determine the generation frequencies occurring during parking to analyze the temporal resolution of the CAM during these maneuvers. The occurring generation frequencies are essential if the CAMs are used in the future as connecting facts in the event of a parking accident.

D. EVALUATION METHODS

Only the message contents of the recorded CAMs were used to evaluate the results of this work. In the following, the applied mathematical calculation rules and methods utilized



**FIGURE 3.** a) Dimensions parking space according to [21], [22] for sideways parking; b) Dimensions parking space according to [21], [22] for forwards and backwards parking.

to analyze the data are presented, as the parameters of interest (generation frequency, distance, trigger conditions) cannot be directly extracted from the contents of the CAMs.

1) CALCULATION OF GENERATION FREQUENCY

The coordinated universal timestamp (UTC) of ROS is used to calculate the generation frequencies of the vehicle's CAMs, which is attached to each message at the reception. First, the time difference  $\Delta t$  between the current timestamp ( $UTC_t$ ) and the time stamp of the previous message ( $UTC_{t-1}$ ) is formed.

$$f_t = \frac{1}{\Delta t_t} = \frac{1}{UTC_t - UTC_{t-1}} \quad (1)$$

Then the frequency is determined by dividing one by the time difference.

2) CALCULATION OF DRIVEN DISTANCES

The distance driven is determined from the longitudinal and lateral position data. For this purpose, the differences ( $\Delta lat$ ,  $\Delta long$ ) at the time of the arrival of a message  $t$  and the previous  $t-1$  between the lateral and longitudinal coordinates ( $lat$ ,  $long$ ) are built.

$$\Delta lat_t = lat_t - lat_{t-1}; \Delta long_t = long_t - long_{t-1} \quad (2)$$

Then, according to [23], the driven distance  $\Delta x_t$  and  $\Delta y_t$  in meter can be calculated by

$$\Delta x_t = 111300 \cdot \cos(lat_t) \cdot \Delta long_t \quad (3)$$

and

$$\Delta y_t = 111300 \cdot \Delta lat_t. \quad (4)$$

Assuming a straight linear movement within the time interval, the Pythagorean theorem can approximately determine the distance  $D_t$  between the two time points.

$$D_t = \sqrt{\Delta x_t^2 + \Delta y_t^2} \quad (5)$$

The sum of all distances  $D_t$  over the total driving time  $T$  results in the experiment's driven distance  $D_{ges}$ .

$$D_{ges} = \sum_{t_0}^T D_t \quad (6)$$

The evaluation shows a distance of 85.2 km for ID.4, 100.9 km for ID.3, and 100.3 km for Golf 8. Compared to the

distances determined by Google Maps in section II-B2, the linear approach chosen to calculate the distance is sufficiently accurate.

3) METHOD TO DETERMINE TRIGGER CONDITIONS

According to section II-A, the trigger values are checked for each message to identify the trigger of the respective message. A change in position of 4 m between two messages can be checked directly by the distance value  $D_t$ , which has already been calculated. The difference values to the previous message ( $t-1$ ) are built to check the change in speed  $\Delta v_t$  and heading  $\Delta \Psi_t$ .

$$\Delta v_t = v_t - v_{t-1}; \Delta \Psi_t = \Psi_t - \Psi_{t-1} \quad (7)$$

For each message, the trigger values are checked according to an if-query and a run variable [ $D_{trig}$ ,  $v_{trig}$ ,  $\Psi_{trig}$ ,  $mixed_{trig}$ ,  $t_{trig}$ ,  $Unknown_{trig}$ ] is incremented by one for the respective trigger if it is true. The order of the query is decisive here since several trigger conditions can be true simultaneously. Thus, all combinations of triggers are checked first ( $mixed_{trig}$ ). Then the individual triggers are checked. If none of the trigger conditions is true, the frequency of the message is also considered. If the frequency is 1.00 Hz, the time trigger has triggered the message ( $t_{trig}$ ). The evaluation has shown that messages that do not fulfill any trigger conditions exist. These are added to  $Unknown_{trig}$ .

Finally, the percentage distribution of the trigger conditions can be calculated from the quotient of the individual run variable with the sum of all run variables. An overview of the formula symbols used is shown in table 1.

**TABLE 1.** List of the formula symbols used.

Symbol	Unit	Description
$f$	Hz	generation frequency
$t$	s	time
$lat$	°	latitude
$long$	°	longitude
$x$	m	x-distance
$y$	m	y-distance
$D$	m	total distance
$v$	m/s	velocity
$\Psi$	°	heading

III. RESULTS

A. REAL-ROAD TEST DRIVE

No data was filtered from the measurement set to evaluate the real-road driving tests. Since the measurement set contains urban and rural areas as well as the highway section, the data of the measurement set must be assigned to the corresponding areas. The assignment was realized with the driven distance  $D_{ges}$  and an evaluation of the distances in the respective areas via Google Maps. By specifying the areas to the driven distance, it was possible to identify and classify each area on the route.

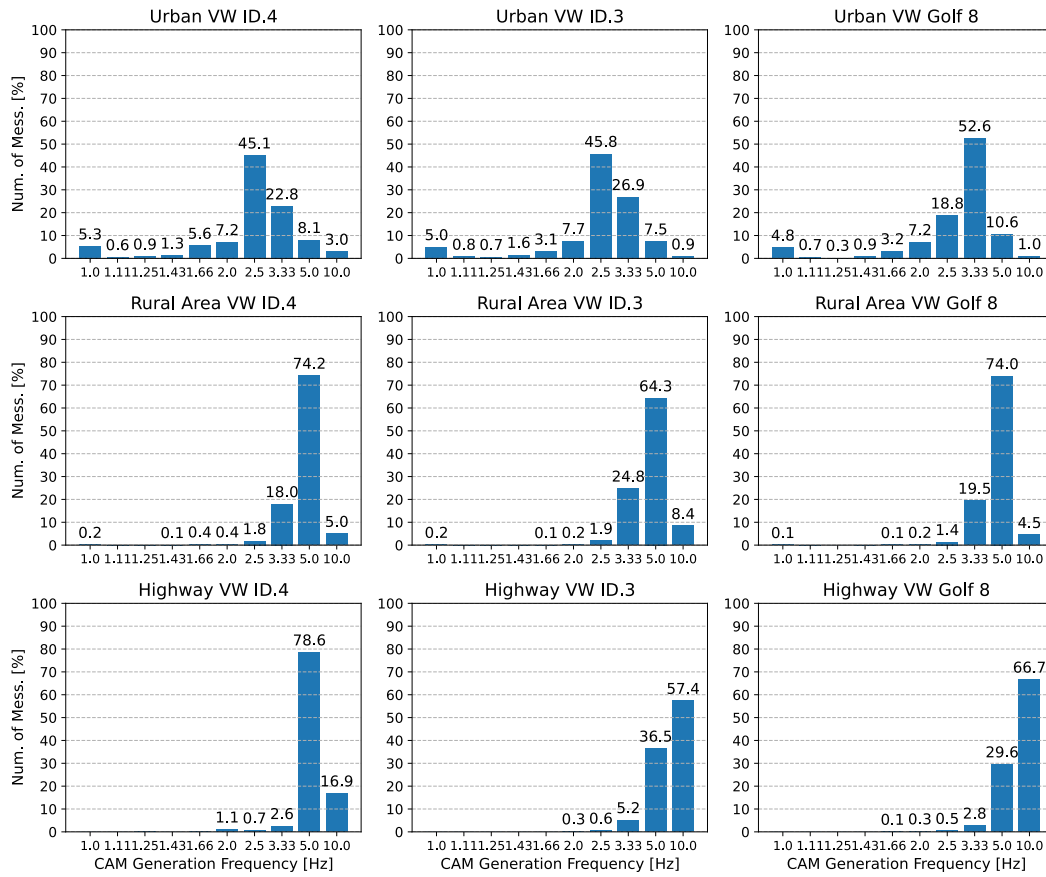


FIGURE 4. Percentage distribution of vehicle generation frequencies in the respective study areas.

Figure 4 shows the resulting generation frequencies of the vehicles in urban and rural areas as well as during driving on the highway. A similar frequency distribution between the vehicles in the respective areas can be noticed. The predominant generation frequency in urban areas is 2.50 and 3.33 Hz and has a share of approx. 70% of the occurring generation frequencies. The greatest scattering of generation frequencies can be observed in urban areas compared to the other investigated areas. The variance is due to the significant influence of the traffic volume, the infrastructure, and a greater variation of the triggers due to turning, accelerating, or braking operations (see figure 5).

Because of higher speeds on rural roads, the predominant generation frequency increases to 5.00 Hz. This value accounts for almost 75% of the generation frequencies that occurred. This is plausible since a large part of the usual speed limit on rural roads (70-100 km/h) in Germany is in the 5.00 Hz range. In addition, the external influences from traffic and infrastructure are low here, which illustrates the low scattering of the generation frequencies.

More than 95% of the generation frequencies on the highway occur at 5.00 and 10.0 Hz. Since there is no speed limit on the investigated highway section during the day, more than 144 km/h were reached, and frequencies of 10.0 Hz were possible. Different traffic densities can explain the difference

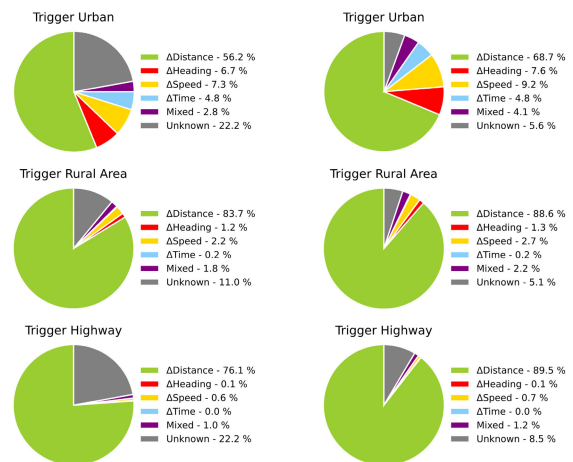
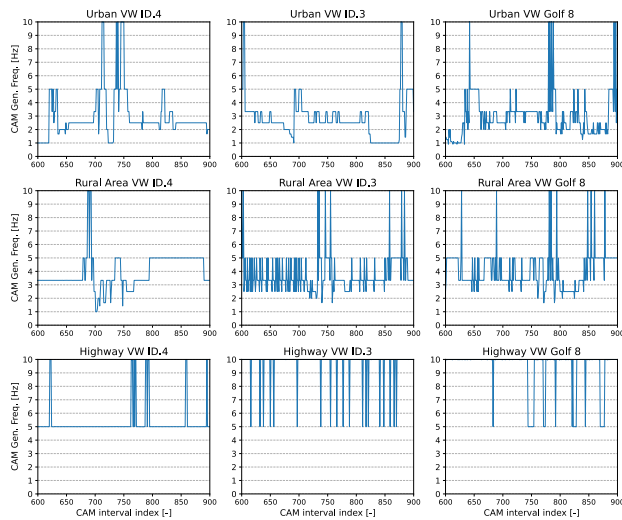


FIGURE 5. Trigger with trigger conditions according to CAM standard (4,4,0.5) in the first column and with 25% reduced trigger conditions (3,3,0.375) in the second column.

in the generation frequencies between the VW ID.4 and the VW ID.3 and Golf 8.

Table 2 lists the average generation frequencies of the test vehicles in the respective areas. In urban areas, mean frequencies of approx. 3 Hz, occur. As expected, mean frequencies



**FIGURE 6.** Excerpt of the CAM's successive generation frequencies of the test vehicles in the respective study areas.

of almost 5 Hz are reached on rural roads. The range of mean frequencies is slightly increasing on highways. However, mean frequencies of about 6 Hz to over 8 Hz could be determined.

**TABLE 2.** Mean value of the generation frequencies of the vehicles in the respective study areas.

Mean Value	VW ID.4	VW ID.3	VW Golf 8
<b>Urban</b>	2.92 Hz	2.80 Hz	3.12 Hz
<b>Rural Area</b>	4.87 Hz	4.94 Hz	4.85 Hz
<b>Highway</b>	5.75 Hz	7.76 Hz	8.27 Hz

The evaluation of the trigger conditions, according to the CAM standard [5], is illustrated on the left pie charts. Figure 5 shows the distribution of trigger conditions across the study areas. In all areas, the distance change trigger (speed) is the main trigger for sending a CAM. This trigger is particularly significant in rural areas and highways, which explains the low scattering of the generation frequencies. As already mentioned, the other triggers or a combination of triggers are mainly found in urban areas.

Unexpected is the large proportion of unknown trigger conditions in all investigated areas. A more detailed evaluation has shown that an unknown trigger often occurs with a jump to higher generation frequencies than the previous message. Therefore, the trigger conditions for all messages with unknown triggers were reduced by 25% in a second step and reassigned. The result can be observed in the right column of figure 5. Many of the unknown trigger conditions change to the distance change trigger. This finding concludes that jumps in the generation frequency towards higher generation frequencies occur shortly before the conditions are actually true. This is especially true for the position change trigger.

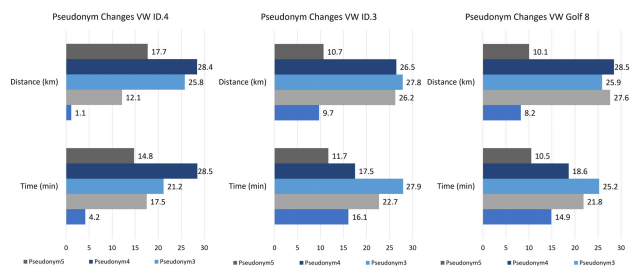
This behavior was already found in the study of the C2C-CC [10] by examining the proportion of repetitive generation frequencies. In the following, a Reevaluation is performed to validate the findings of the C2C-CC for the vehicles on the market. Figure 6 shows the result of this evaluation. The generation frequencies of the successively sent CAM messages were illustrated for the test vehicles via the test environments. The figure shows only a small section of 300 messages as a representative example.

The jumps in the generation frequencies are recognizable by peaks. The peaks and, thus, the frequency jumps occur in all test environments. Considering table 3, this can be further quantified by analyzing the percentage of repeating generation frequencies. The jumps occur mainly in urban areas and decrease towards the highway. It is also evident that the jumps are related to the vehicle development age. Besides the highway, Golf 8 shows the worst result for generation frequency fidelity. The generation frequency fidelity increases over ID.3 and ID.4. With the increasing development of the vehicles and, thus, the implemented V2X technology, the jumps seem to decrease. The fact that approx. 50% of the frequencies are erratic, as in the study by the C2C-CC [10], can only be confirmed for the Golf 8 in the urban area.

**TABLE 3.** Mean value of the percentages of the repetitive generation frequencies.

Mean Value	VW ID.4	VW ID.3	VW Golf 8
<b>Urban</b>	74.0 %	79.9 %	51.6 %
<b>Rural Area</b>	95.7 %	86.6 %	68.2 %
<b>Highway</b>	95.4 %	88.3 %	92.6 %

Lastly, the pseudonym change of the vehicles in road traffic was investigated with the data. Figure 7 shows the distance and time driven per pseudonym. All vehicles had five different pseudonyms over the whole test drive. To evaluate the reason for the change of pseudonym, the first and last pseudonym must not be used, as the measurement was started or stopped here, and the local and temporal sequence is incomplete.



**FIGURE 7.** Distance and time to pseudonym change per vehicle.

Despite that, the middle three pseudonyms do not show an apparent reason for the pseudonym change in space and time. The time that elapses before a pseudonym change varies

between 17.5 and 28.5 min. The range of distance driven varies from 12.1 to 28.5 km. From a security point of view, it is commendable that the change of pseudonyms takes place in a value range, making tracking more difficult.

## B. PARKING MANEUVERS

Before evaluating the parking maneuvers tests, the measurement data were filtered only to consider the actual parking procedure. Accordingly, all measurement data with velocities < 1 m/s in the tests were filtered out. These filters could be determined by visual inspection of the time curves. Figure 8 illustrates the percentage distribution of the generation frequencies over the tests per vehicle and parking maneuver. The distribution shows a significant scattering over all possible generation frequencies. For backwards and forwards parking, the distribution resembles an upward-opening parabola with high relative shares at 1.00 Hz, 3.33 Hz, and 5.00 Hz. In contrast, larger proportions of the lower frequencies are found for parking sideways. In addition, the proportion of the 1.00 Hz frequency is the most frequent for each vehicle in the respective parking maneuvers.

Despite the same driver and test set-up in all tests, there are larger differences in the distribution of the generation frequencies between the vehicles in the respective tests. For example, the proportion of 1 Hz during backwards parking for ID.4 and ID.3 is over 30%, while the proportion of 1.00 Hz generation frequency of the Golf 8 is only 17.2%. This indicates that the actual distribution of the generation frequencies also depends on the vehicle. The deviation could be due to the slightly smaller width of the Golf 8 in contrast to the ID.3 and ID.4 [24], which made parking easier and more dynamic. Nevertheless, the same basic pattern of the generation frequency distribution can be observed in all tests for all vehicles.

Table 4 shows the mean value of the generation frequencies for each vehicle per test. The average generation frequency for backwards parking ranges from 3 to 4 Hz. For forwards parking, average frequencies of around 3 Hz can be found. When parking sideways, the average generation frequencies are lower and range from 2.1 to 2.7 Hz.

**TABLE 4.** Mean value of the generation frequencies of the vehicles in the respective study areas.

Mean Value	VW ID.4	VW ID.3	VW Golf 8
Backwards	3.07 Hz	2.94 Hz	4.17 Hz
Forwards	2.82 Hz	3.23 Hz	3.21 Hz
Sideways	2.11 Hz	2.67 Hz	2.56 Hz

Considering the trigger conditions according to figure 9, a completely different result can be observed than in the real-road driving tests. In the parking tests, the position change trigger accounts for only 3 to 4% of the trigger shares. The change in heading is significant for forwards and backwards parking if the time trigger for 1.00 Hz is ignored. On the other hand, the speed change trigger accounts for about 10 to

15% of the trigger proportions. This distribution changes with sideways parking. There, the speed changes are decisive in addition to the time trigger, which is plausible since sideways parking requires a smaller angle for the parking maneuver than backwards and forwards parking. In addition, a significant proportion of mixed trigger conditions can be seen for sideways parking.

Analogous to the trigger distribution in figure 5, more significant proportions (approx. 25%) of the trigger conditions are unknown. If the trigger condition is reduced by 25% and the percentages are newly calculated, the proportion of unknown triggers is reduced to approx. 15%. The unknown shares are transferred to the heading and speed change trigger to approximately the same extent. Nevertheless, a larger percentage of unknown trigger conditions remains here compared to the real-road driving tests.

## IV. DISCUSSION

A diverse distribution of generation frequencies can be determined in the urban area. This result agrees with Observation 9 from the C2C-CC study [10] that the generation frequency depends on many factors. This only applies to the urban area and should not be assumed in general. The most frequent single frequencies are 2.5 and 3.33 Hz, which is plausible based on the predominant position change trigger (speed). This finding is also consistent with Observation 10 of the C2C-CC. Nevertheless, this again only applies to the urban area. The average generation frequency across all vehicles in the urban area is 2.95 Hz (see Table 5). This represents an improvement of almost 50% compared to the temporal resolution of the EDR in the pre-crash phase in the event of an accident.

It must be noted that the generation frequencies in urban areas strongly depend on many parameters, which can be seen in the significant variance of the generation frequencies. In addition to the influence of the environment, the driver also significantly influences the generation frequencies occurring in the urban area, as his driving style also plays a role here. Since the same driver carried out the tests in this study, it is not yet possible to draw any conclusions about the generation frequencies of the normal driver in the urban area. This also applies to the other test scenarios, especially if the vehicle's speed does not cause the generation frequencies of the CAM. On the other hand, it can be assumed that the normal driver complies with the applicable speed limit, and thus the generation frequency occurs for this speed.

Compared to the urban area, a completely different result was found for the occurring generation frequencies on rural roads. Approximately 75% of the generation frequencies are at 5.00 Hz, which is plausible due to the low traffic volume and lack of infrastructural influence. This is further illustrated by the very high proportion (> 80%) of the position change trigger (speed). Accordingly, the average generation frequency over all vehicles on the rural road is 4.89 Hz (see Table 5). The mean generation frequency of the CAM corresponds to an improvement in the temporal resolution of



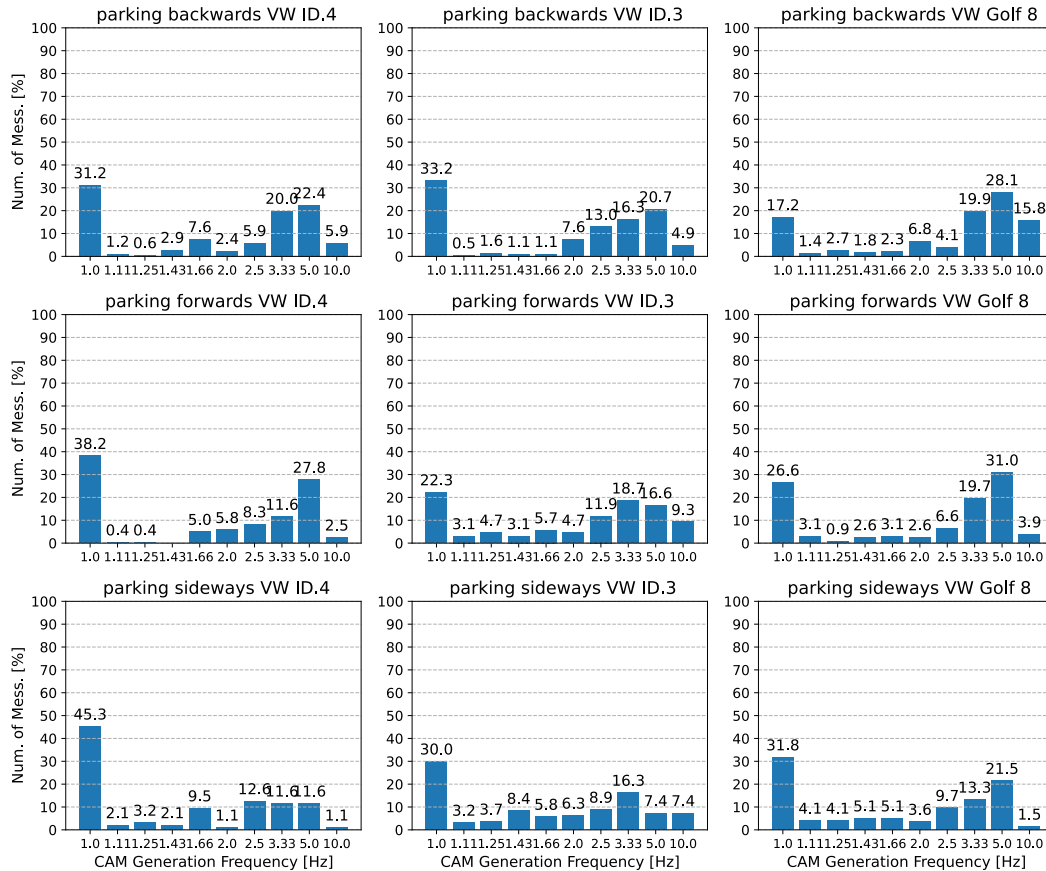


FIGURE 8. Percentage distribution of the generation frequencies of the vehicles at the respective parking maneuvers.

TABLE 5. Summary of the mean values and standard deviations of the generation frequencies per examined operating scenario.

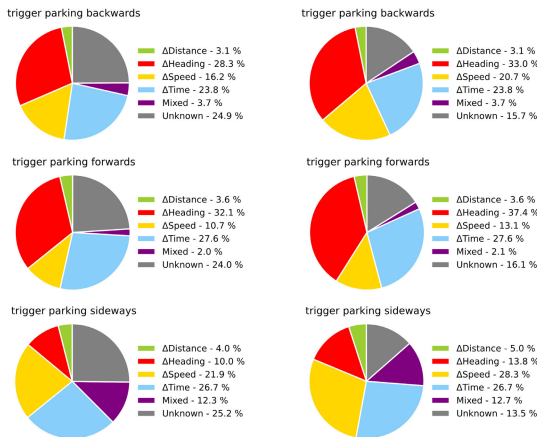
Scenario	Urban	Rural Road	Highway	Backwards	Forwards	Sideways
Mean Value	2.95 Hz	4.89 Hz	7.26 Hz	3.39 Hz	3.09 Hz	2.45 Hz
Standard Deviation	1.28 Hz	1.49 Hz	2.36 Hz	2.48 Hz	2.24 Hz	1.93 Hz

the pre-crash phase in the event of an accident by a factor of 2.5. In addition, these frequencies can be expected in general since they significantly depend on the speed limits on rural roads, and hardly any other influencing factors interfere with them. According to [8], almost 60% of all fatal accidents in Germany occurred on rural roads in 2021, although only 21% of accidents occurred there. Improving the temporal resolution on rural roads could thus improve the clarification of severe accidents with fatalities.

An even higher average generation frequency is found on highways. Due to German highways' lack of speed limits, significant proportions of 10.0 Hz generation frequency can be found. 95% of the generation frequencies are at 5.00 or 10.0 Hz. On average, a generation frequency of 7.26 Hz could be determined for all vehicles (see Table 5). This generation frequency corresponds to an improved temporal resolution of a possible accident scene of 3.5 compared to the EDR. However, it must be stated that the high proportion of 10.0 Hz generation frequency will not be achieved on speed-limited

highways, as the limit is for two exceptions (Germany and Australia's Northern Territory) 140 km/h and less worldwide, which is below the threshold value of 144 km/h for 10.0 Hz generation frequency for the position change trigger [25]. In addition, the frequencies found only apply to average traffic volumes. In congested traffic, lower speeds are driven, and thus generation frequencies are reached.

Regarding the trigger conditions, it should generally be noted that the speed of the vehicles is decisive for the generation frequency in all three study areas. Traffic and infrastructure (traffic lights, traffic signs) affect the vehicle's speed and greatly influence the realized generation frequency. The driver only has a minor influence if he sticks to the applicable speed limits. A larger proportion of CAMs with unknown triggers was also found, which missed the position change (speed) trigger by a small margin. The unknown triggers near the distance change trigger could be explained by inaccuracies in GPS positioning but need to be investigated in more detail.



**FIGURE 9. Trigger with trigger conditions according to CAM Standard (4,4,0.5) in the first column and with 25% reduced trigger conditions (3,3,0.375) in the second column for parking maneuvers.**

Regarding the change of pseudonyms, no clear result could be obtained at first. Considering the technical specification 102 941 [26] from ETSI, the second pseudonym change of ID.4 could also be due to an Authorization Ticket request, resulting in a change of all other identification numbers. It is noticeable that all other pseudonym changes occur between 25 and 29 km. This may be the distance range for triggering a pseudonym change implemented by Volkswagen.

Since according to [27], there are no requirements in space and time on behalf of ETSI for pseudonym change, Volkswagen's chosen implementation cannot be measured against it. As the report was already published in 2018, all relevant standards and technical specifications were searched again for requirements [26], [28], [29], [30]. Nevertheless, no requirements for triggering a pseudonym change in space and time were still found. In [27], different approaches for the pseudonym change are summarized. For example, the C2C-CC recommends changing the pseudonym every 800 m or 2-6 min. Volkswagen's implementation deviates from this significantly, and the pseudonym change is carried out much less frequently. Although ETSI has no requirements for the local and temporal change of pseudonyms, it is still critical to question why this is so rarely carried out compared to the recommendation of the C2C-CC. Since this work does not deal with IT security, this point will not be discussed further.

In the parking tests, a moderate improvement of the mean temporal resolution could be determined compared to the EDR in the pre-crash phase of an accident. For backwards parking, a mean frequency of 3.39 Hz is achieved across all vehicles and tests. For forwards parking, a mean frequency of 3.09 Hz and 2.45 Hz for sideways parking could be determined (see Table 5). The time trigger (1.00 Hz) and the heading and speed change trigger, which cause larger generation frequencies (3-10 Hz), have a large proportion of the trigger conditions. The more significant scattering of trigger conditions for all parking maneuvers indicates a substantial dependence on the individual parking situation and the driver for the realized generation frequency.

It should generally be noted that although the determined generation frequencies are significantly dependent on the environment and the driver, other communication-related parameters can influence the generation frequency. As described in [31] and [32], the generation frequency also depends on the channel load and the implemented security protocols. Again, The channel load depends on the generation frequency, the message size, and the vehicle density of communicating vehicles [31], [33]. The decentralized congestion control method, specified in TS 102 682 [34], implements a safety mechanism that reduces the generation frequency when the channel load is high [35]. Accordingly, high channel loads are conceivable in urban environments and motorways due to high traffic density, making them often the chosen environment for V2X performance tests [36], [37]. Since, in this study, only a few other V2X-capable vehicles were recorded, the measured generation frequencies are independent of the channel load. Thus, with a high market penetration of the systems and a possible co-use of the V2X bandwidth for mobile edge computing, as proposed in [32], high channel loads are very likely, which can negatively influence the generation frequencies in urban areas, in parking, and on highways.

Lastly, it should be noted that the results found are not yet statistically significant. For this, large-scale user studies should be conducted to determine the "normal driver" generation frequencies in the investigated driving situations and environments. Conducting studies is especially necessary for urban areas and parking maneuvers. In addition, this work has only involved vehicles from the manufacturer Volkswagen, and the results depend on their implementation. The fact that the results can vary is shown by the reduction in frequency jumps towards newer models at Volkswagen itself. But, significant differences between the manufacturers in the generation frequencies and triggers of the CAM are not expected, as these are standardized. Also, studies with a high channel load would be interesting for future work.

## V. CONCLUSION

This work investigated the CAM's generation frequencies, its causing triggers, and pseudonym changes of V2X vehicles on the European market under real operating scenarios. The objective is to determine if, in the event of an accident, the generation frequency of the CAM offers a higher temporal resolution during the accident scene than the EDR. Besides the extra data provided by the CAM compared to the EDR, a higher temporal resolution of the accident scene could significantly contribute to its reconstruction and clarification. For this purpose, tests were conducted on a real driving route and the test area of the CARISSMA near Ingolstadt. The driving route was divided into urban and rural areas as well as highways. Also, parking tests (backwards, forwards, and sideways) were conducted on the test site.

It was found that in all operating scenarios, the temporal resolution of the accident scene of the CAM would be better than that of the EDR. Particularly on rural roads and

highways, the CAM has a much greater temporal resolution based on the generation frequency (factor 2.5 to 3.5), explainable by the mainly occurring distance change (speed) trigger. On the other hand, the advantage in parking maneuvers is minor and largely dependent on the parking situation itself, the vehicle, and the driver. Here, the heading and speed change triggers are the most significant. For Volkswagen's implemented pseudonym change algorithm, it was found that the pseudonym change takes place with a high probability between driven distances of 25 to 29 km. Due to a deviating value, this must be verified by further tests.

The observed variance in generation frequencies implies that various environmental factors and the driver's behavior significantly impact the achievable generation frequencies, particularly when driving in urban areas or parking. In environments where the position change trigger, and subsequently the speed is decisive, the aforementioned influences decrease. Nevertheless, the results already provide information about the generation frequencies that can be achieved in various real operating scenarios. Additional large-scale user studies could further validate these.

Regarding accident analysis, it can be concluded that the storage of CAM data would enhance the temporal resolution of a potential accident scene across all the investigated areas. Accordingly, further research and development efforts should be invested in exploiting CAM as digital data for accident analysis. Due to the high number of parking accidents, increasing the CAM generation frequency during parking would also be desirable. In addition, V2X communication offers many other messages and, thus, information that can support the clarification of accidents. Exploiting this additional data from the V2X Communication could be a further benefit for clarifying accidents in the future.

## ACKNOWLEDGMENT

The authors would like to thank the company FSD Fahrzeugsystemdaten GmbH for providing the test vehicles. They would also like to acknowledge the support during the tests and the provision of software and measuring equipment by our colleagues Silas Lobo, Michael Weinzierl, and Christian Gudera.

Author Contributions: Maximilian Bauder: Conceptualization, methodology, software, validation, formal analysis, investigation, writing (original draft), visualization, and funding acquisition. Tibor Kubjatko: Validation, writing (review and editing), and supervision. Hans-Georg Schweiger: Validation, writing (review and editing), supervision, and project administration. All authors have read and agreed to the published version of the manuscript.

## CONFLICTS OF INTEREST

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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**TIBOR KUBJATKO** was born in Āilina, in 1966. He studied at the University of Transport and Communications, Āilina, from which he graduated in operation and economics of road and urban transport, in 1988. He received the Ph.D. degree in forensic engineering from the University of Āilina, in 2001, and the L.L.M. degree from the European Institute of Law and Judicial Engineering, Czech Republic, in 2021. He is one of the leading European experts in the field of forensic sciences

and road transport safety. In his academic career, he teaches courses in forensic engineering, technical diagnostics and repair, estimation of the value of road vehicles and calculation of damages, and methodology of expert experiments. He is an Expert registered in the list maintained at the Ministry of Justice of the Slovak Republic for Road Transport and also a Mechanical Engineering. He is also an Auditor of road safety, with professional competence for the activity: Evaluation of critical accident sections of road by on-site inspection. To date, he has organized and carried out more than 120 crash tests for forensic investigations, a large part of them abroad. He is a member of the Scientific Board of the IFRE UNIZA, a member and the Vice-Chairman of the working group of the Doctoral Studies Committee for the field of forensic engineering. As a Supervisor and a Specialist, he trained 12 Ph.D. students, many of them are leading European experts. He is the author or coauthor of several important methodologies for forensic activities in road transport, accident analysis, diagnostics and repair, and vehicle valuation. He has also been and is the principal investigator and responsible for several major national and international projects. He is the author or coauthor of more than 50 scientific and technical articles. He holds the position of Deputy Director and a University Lecturer at the Institute of Forensic Research and Education, University of Āilina (IFRE UNIZA). He is the Secretary of the European Association for Accident Research and Analysis (EVU), Berlin.



**HANS-GEORG SCHWEIGER** (Member, IEEE) was born in Ingolstadt, in 1977. He received the Dipl.-Chem. degree in chemistry from the University of Regensburg, Germany, in 2002, the Ph.D. degree in electrochemistry from the Workgroup of Prof. Heiner J. Gores, University of Regensburg, and the Dr.rer.nat. degree in chemistry from the University of Regensburg, in 2004. He joined EVA Fahrzeugtechnik GmbH (Munich) as a Development Engineer for HEV energy storage systems,

in 2005. In this position, he was appointed as an Engineering Consultant to BMW AG, Munich, Germany. In January 2007, he joined the HEV Department, Continental AG, Berlin, Germany. In this company, he worked as an Expert for lithium-ion batteries. In 2008, he was appointed as a Project Leader for energy storage systems at Continental AG. In this position, he was leading a series of development projects for HEV and EV battery systems as well as one basic research project for the development of 5 V lithium-ion cells. He was also a part-time Lecturer on electrochemical energy storage systems at the Technical University of Berlin, from 2009 to 2011. He was appointed as a Professor of automotive electronics and electric mobility at Technische Hochschule Ingolstadt, in 2011. He founded the research group “Safe Electromobility.” In 2020, this research group was transformed into CARISSMA Institute of Electric, Connected and Secure Mobility. Since then, he is the Head of this research Institute. The primary field of his group are energy storage systems for automotive applications, the safety of electric vehicles, and accident forensics. His workgroup of about 20 coworkers is working on industry and government-financed research projects in the field of automotive energy storage systems. He is also the Director of study programs in the field of electric engineering and electric mobility. He is the author/coauthor of more than 50 research articles and he holds 20 patents. He is a member of VDE and VHB.



**MAXIMILIAN BAUDER** was born in Ingolstadt, Bavaria, Germany, in 1995. He received the B.Eng. and M.Eng. degrees in mechanical engineering from Technische Hochschule Ingolstadt, Ingolstadt, in 2019 and 2021, respectively. He is currently pursuing the Ph.D. degree in cooperation with the University of Āilina, Slovakia. Since 2021, he has been a Research Assistant at the Center of Automotive Research on Integrated Safety Systems and Measurement Area (CARISSMA),

Technische Hochschule Ingolstadt. There, he works in the Forensic Research Group of Prof. Dr.rer.nat. Hans-Georg Schweiger at the CARISSMA Institute of Electric, Connected and Secure Mobility (C-ECOS). Currently, he is the author or coauthor of seven research articles. His research interests include accident analysis, accident research, vehicle-2-X communication, advanced driver-assistance systems (ADAS), and vehicle safety in general. His research interests include the influences of vehicle communication, automation, and electrification on accident analysis.