

Data accuracy in Vehicle-to-X cooperative awareness messages: An experimental study for the first commercial deployment of C-ITS in Europe

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ABSTRACT

Cooperative Intelligent Transportation Systems have achieved a mature technology stage and are in an early phase of mass deployment in Europe. Relying on Vehicle-to-X communication, these systems were primarily developed to improve traffic safety, efficiency, and driving comfort. However, they also offer great opportunities for other use cases. One of them is forensic accident analysis, where the received data provide details about the status of other traffic participants, give insights into the accident scenario, and therefore help in understanding accident causes. A high accuracy of the sent information is essential: For safety use cases, such as traffic jam warning, a poor accuracy of the data may result in wrong driver information, undermine the usability of the system and even create new safety risks. For accident analysis, a low accuracy may prevent the correct reconstruction of an accident. This paper presents an experimental study of the first generation of Cooperative Intelligent Transportation Systems in Europe. The results indicate a high accuracy for most of the data fields in the Vehicle-to-X messages, namely speed, acceleration, heading and yaw rate information, which meet the accuracy requirements for safety use cases and accident analysis. In contrast, the position data, which are also carried in the messages, have larger errors. Specifically, we observed that the lateral position still has an acceptable accuracy. The error of the longitudinal position is larger and may compromise safety use cases with high accuracy requirements. Even with limited accuracy, the data provide a high value for the accident analysis. Since we also found that the accuracy of the data increases for newer vehicle models, we presume that Vehicle-to-X data have the potential for exact accident reconstruction.

1. Introduction

Cooperative Intelligent Transport Systems (C-ITS) use information and communication technologies to transport people and goods [1]. Vehicle communication with its environment (V2X) is an important technology of C-ITS and is differentiated into communication with other vehicles (V2V), with intelligent infrastructure (V2I), or with people (V2P) [1,2]. The current Release 1 of standards for C-ITS defines two core services, i.e. the Cooperative Awareness Basic Service (CA) and the Decentralized Environmental Notification Basic Service (DEN). These two services are also part of the initial C-ITS deployment and are integrated into V2X-enabled vehicles. For both V2X communication services, dedicated message types, which are generated by vehicles and transmitted to other vehicles, are defined [3,4]. The CA service message type is called Cooperative Awareness Message (CAM) and is sent by each vehicle one to ten times per second [3]. The message content contains

status information about the vehicle itself and realizes various safety-related applications such as longitudinal / intersection collision risk warning (LCRW and ICRW) and other use cases [3,5,6]. The accuracy of the information is of great importance to have high robustness against false-positive and false-negative triggers. For example, with the CAM position information, an overlap of the longitudinal alignment can be calculated, which is a basic requirement for detecting a collision risk. If many false-positive warnings occur, user acceptance can be harmed. If, on the other hand, there are no warnings due to false-negatives, the safety gain by the applications is greatly reduced.

The CAM is also a valuable source of accident data in the accident analysis [7]. If an accident occurs, the accident scene is reconstructed according to the current state of the art using classical connecting factors such as skid marks, impact marks on the road, and vehicle deformations. By applying classical laws of physics, such as the laws of conservation of energy and conservation of momentum, the accident scene can be

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determined approximately. More modern vehicles equipped with an event data recorder (EDR) can provide additional digital traces for accident reconstruction. However, only the speed information in the EDR is useful for reconstructing the accident scene. In contrast, the data carried in CAM provide information about the position, speed, heading, yaw rate, and longitudinal acceleration of the vehicles involved in an accident [7]. They can be particularly useful in reconstructing an accident scene, as the described classic accident data, such as skid marks, are diminishing due to increasing vehicle automation. In addition, the tolerance of the accident reconstruction based on crash-mechanical equations (momentum and energy theorem) is constantly increasing due to regulating actions of driving assistant systems in case of a crash. An open point for the exploitation of V2X data for accident analysis is the evaluation of the technical significance of the data, which was shown using the schematic framework in [7].

An additional non-safety application that could benefit from the findings in this work is V2X tolling. According to [8], the lateral position accuracy is of great importance to assign vehicles to the respective lane for correct tolling. Therefore, knowledge of the lateral positional accuracy of the CAM data could also improve this field of research. However, V2X tolling will only be mentioned here and would not be discussed further in this work.

However, the current problem with using V2X data for accident analysis is the unknown accuracy of the data. In court, the accident analyst must always specify a tolerance range in the accident reconstruction he has performed. Therefore, to actually use the V2X data for accident reconstruction, the accuracy of the data must be determined.

Thus, this work aims to investigate and to evaluate the accuracy of the CAM data in V2X-capable series vehicle to demonstrate their (legal) usability for accident analysis. At the same time, it can be investigated whether the achieved accuracies are sufficient to meet the requirements of current safety-relevant use cases. It is also intended to determine whether the accuracy of existing parameters for accident analysis can be further improved. In addition, the message generation frequencies of CAMs occurring in different well-defined scenarios will be determined to generate further data for accident analysis. For the purpose of this work, driving tests were carried out at the test site of the Center of Automotive Research on Integrated Safety Systems and Measurement Area (CAR-ISSMA) of the Ingolstadt University of Applied Sciences with vehicles on the European (EU) market that are equipped with V2X technology. The focus was on the accuracy of the data under consideration of the dynamics of the vehicles. Three V2X-capable series vehicle models – Volkswagen Golf 8, ID.3, and ID.4 – which were available on the EU market at the time of the study in 2022, were investigated. Since there were no other vehicles with V2X on the EU market at the time of data collection, no other vehicles from other manufacturers could be studied. However, it can be assumed that the technology and, thus, accuracies hardly differ between the manufacturers. This is necessary to ensure interoperability between the manufacturers' vehicles. In addition, the hardware components are often installed in the manufacturers' vehicles by the same suppliers. In addition, a highly accurate reference measurement system was used in the vehicles to generate a ground truth for position and time data. The collected data were processed by a specifically developed Robotic Operating System (ROS)-based measurement environment and stored during the measurement.

In a previous study by the Car 2 Car Communication Consortium (C2C–CC) [9], the statistical properties of the transmitted CAM data were investigated and test drives with vehicles from two manufacturers with their respective V2X implementations were compared. The focus of the study was on the statistical distribution of the CAM data size values and the time interval values between two messages (generation frequency). The message size showed a continuously fluctuating number of bytes over time for all test drives, varying between 200 and 800 bytes. Interestingly, the values were particularly dependent on the manufacturer and not on the vehicle drivers. On average, a message size of approx. 350 bytes was determined. The time interval analysis showed

that messages were always generated in multiples of 100 ms intervals, which is due to the checking of the trigger conditions in 100 ms intervals. The resulting generation frequency is 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 is between 0.33 and 0.47 s and is generally very dependent on the respective driving scenario.

Another study in [10], collected CAMs on a real test track to assess vehicle speed and acceleration data. The objective was to detect changes in speed and braking events without using further sensors in the vehicle that receives the CAMs. It turned out that speed changes can be detected well based on CAM data, but brake events based on acceleration data are more difficult due to the measuring noise. Compared to the present work, the accuracy of the measured data were not examined. The study also announced further tests with accelerometer and CAN bus logger as future work, but this has not been realized yet.

Many other existing studies addressed the system performance of CAMs and compared the performance of the two competing access technologies [11–14]. However, these aspects are not the focus of the present work.

In summary of the related work, we can state that some studies have already dealt with the evaluation of the statistical properties of CAMs. However, the investigation of the accuracy of the CAM content, especially with V2X-capable vehicles available on the EU market, has not been carried out. Concerning the investigation of the C2C–CC, the generation frequency of vehicles on the market can also be checked.

2. Theoretical background, experimental and methods

2.1. Vehicle-2-X communication

2.1.1. Structure and parameters of the cooperative awareness message

The Cooperative Awareness Message (CAM) is a message type standardized by the European Telecommunication Standardization Institute (ETSI) as part of Release 1 for the European C-ITS. Following the standard, a CAM is periodically sent 1 to 10 times per second by a V2X-capable vehicle as soon as it is in a “safety-related context”, i.e., it is activated [3]. The message contains status information about the sending vehicle itself. It enables the receiving vehicles to determine their presence in space and time as well as their current dynamics. The structure of the message and the containing parameters is depicted in Fig. 1. The CAM consists of five containers, which have parameters that are either mandatory, optional or both.

This investigation focuses on the mandatory parameters, as these must be included in every CAM and are, therefore, always available for accident reconstruction. Initial measurements with the test vehicles also confirmed that only the mandatory parameters were sent and the optional parameters omitted. From the mandatory parameters, the parameters *ReferencePosition*, *Heading*, *Speed*, *LongitudinalAcceleration*, and *YawRate* are analyzed. To every parameter, accuracy information for the actual value is appended, which should improve the confidence of the receiving vehicle in the data. However, the measurements revealed that only the accuracy of the heading value was carried in the messages; the other accuracy data were missing. Consequently, in the evaluation, only the available accuracy values were considered. One reason for the non-availability could be the low confidence of the system in the accuracy of the other parameters, as this must be at least 95% according to the standard [3]. Also, it could not have been implemented by the manufacturer.

In addition to the accuracy of the parameters, the message generation frequency should be considered. According to [3], a CAM is transmitted with minimum of 1 Hz and maximum of 10 Hz, whereas the actual frequency depends on the vehicle dynamic based on trigger conditions: A CAM is generated as soon as the vehicle experiences a change in the direction of travel of 4°, the position of 4 m or speed of 0.5 m/s compared to the previous CAM transmission. These values

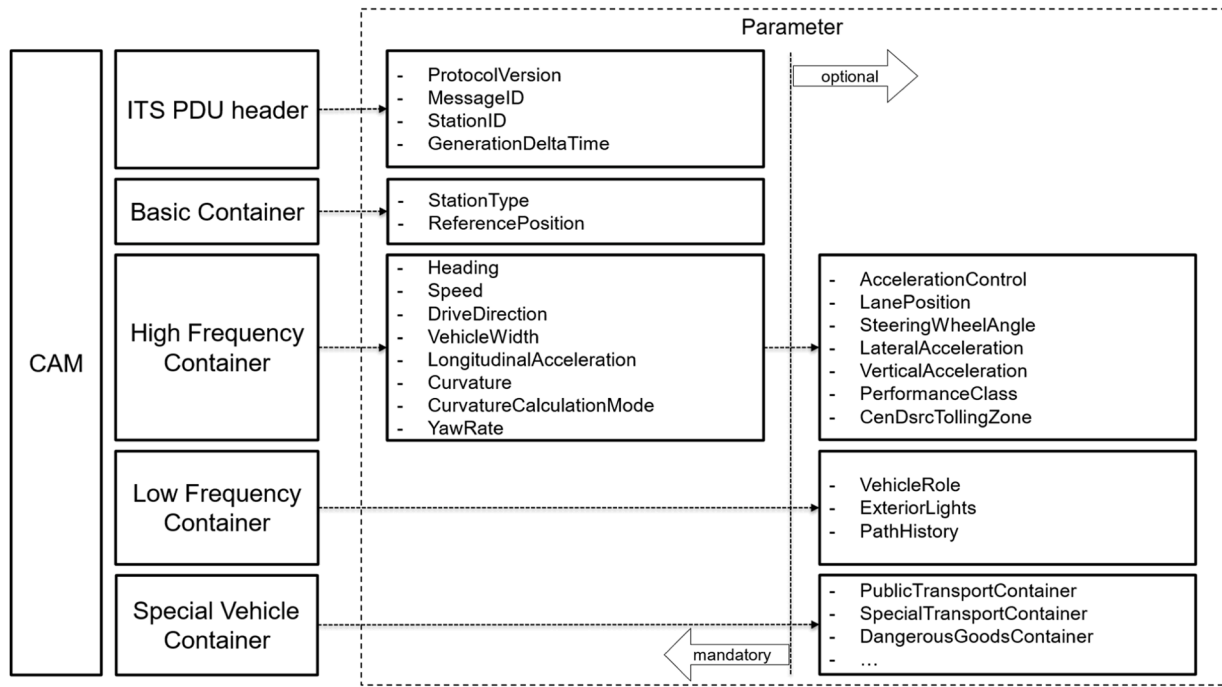


Fig. 1. Structure of the Cooperative Awareness Message according to [3] with presentation of the mandatory and optional parameters.

correspond to a speed of 40 m/s (~ 144 km/h), an acceleration of 5 m/s², or a yaw rate of 40°/s. The trigger conditions are checked every 100 ms. A CAM is also sent if no trigger is activated within 1000 ms.

2.1.2. Cooperative awareness message accuracy requirements

To evaluate and classify the determined accuracies, requirements are essential. The CAM standard [3] does not specify requirements for the accuracy of the parameters.

For the safety-relevant applications LCRW and ICRW, requirements regarding position accuracy have been specified in the respective standards. For LCRW, a position accuracy of more than or equal to 1 m is required [5]. The ICRW demands an accuracy of more than or equal to 2 m [6].

The C2C—CC publishes the Basic System Profile (BSP) at irregular intervals [15]. In addition to a list of the relevant base standards and its parameter setting, the BSP comprises requirements for the data quality of important – so called ‘Day 1’ – use cases of V2X communication. However, it should be noted that none of the BSP specifications contain requirements for the accuracy of CAM data.

Concerning accident analysis, there are no specific requirements for accuracy, as this varies depending on the type of accident, on the available accident data, and on the experience of the accident analyst [16,17]. Information on the accuracy of reconstruction parameters according to the current state of the art is only available regarding collision speed. According to [16], experienced accident analysts should be able to estimate the speed with an accuracy of ± 5 km/h based on the deformations of the vehicles involved in the accident. According to [17], it should be possible to determine the collision speed of a vehicle with a pedestrian with the same accuracy if the throw distance is known. Since mid-2022, the Event Data Recorder (EDR) has been mandatory for new vehicle models in Europe [18]. Here, the speed and other parameters, which cannot be found in the CAM, are stored by the EDR up to 5 s before impact [19]. The accuracy of the speed information is said to be ± 1 km/h, although independent tests in the literature have not verified the achieved accuracy yet. In a more recent study [20], the accuracy of collision speeds reconstructed with the help of police reports was determined with an additionally installed reference black box. A mean error of 9.03 km/h was determined for the reconstructed speeds.

Compared to [16], the findings of [20] show that the actual achieved accuracy of the velocity by the classical reconstruction is above 5 km/h. Nevertheless, the ± 5 km/h from [16] shall be used as the speed accuracy requirement of the CAM for this work to set stricter requirements on the accuracy to be achieved. Thus, an error of less than 5 km/h improves the accident analysis if no EDR is installed. With EDR, the accuracy of the speed information in the CAM should be better than 1 km/h.

2.2. Experimental set-up

For the realization of the measurements, a measurement set-up was built, which was used identically in the respective vehicles and is illustrated in Fig. 2. The CAMs of the test vehicles are fed into the measuring computer by a V2X communication module from the company Commsignia [21], a well-known supplier of V2X devices and V2X software protocol stack. The measuring computer runs ROS Noetic on Ubuntu 20.04. In addition, reference data are generated by an Automotive Dynamic Motion Analyzer (ADMA-G-PRO+) from the Offenburg (Germany)-based manufacturer GeneSys [22] and also processed in the ROS software environment. ROS automatically timestamps all data as soon as the system receives them. For a high temporal resolution, the reference data of the ADMA are sampled at 100 Hz. Depending on the trigger mechanism described, the CAM data are generated by the vehicle, received, and stored in the ROS software environment with a timestamp.

2.2.1. Test vehicles description

All V2X-capable test vehicles that were already available on the EU market at the time of the tests were examined. Since Volkswagen only uses V2X technology in Europe, the Golf 8, ID.3, and ID.4 models were investigated. Table 1 lists the test vehicles with the installed software version at the measurement time. Other relevant vehicle parameters are the installed engine and its power and the vehicle mass, as these are directly related to the vehicle’s dynamic behavior. All vehicles send messages based on WLANp (ITS-G5, DSRC). Implemented services are the Cooperative Awareness Basic Service and the Decentralized Environmental Notification Basic Service. Volkswagen does not provide an overview of the implemented use cases.

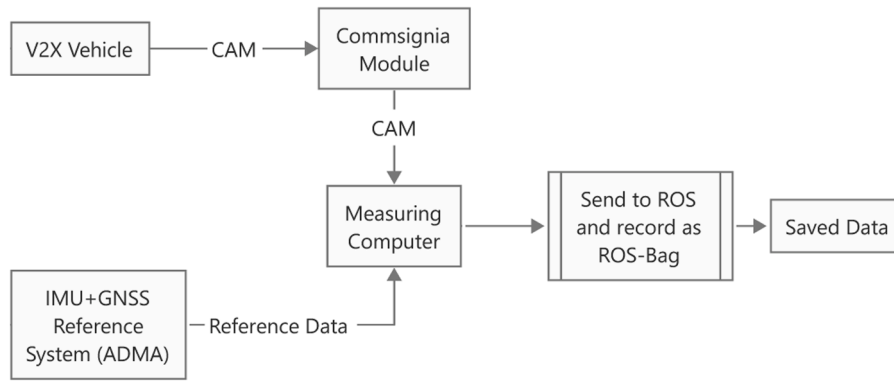


Fig. 2. Schematic representation of the measurement set-up for measuring and storing the data.

Table 1

List of test vehicles and software status at the time of the measurements.

Test Vehicle	VW Golf 8 GTD	VW ID.3 Pro 150 kW	VW ID.4
Engine	Diesel	Electro	Electro
Total Power [kW]	147 / 3600	150	150
Curb Weight [kg]	1466	1805	2151
Software Version	1890	0910	0792

Fig. 3 shows the realization of the schematic measurement set-up from Fig. 2 using the VW ID.4 as an example. Fig. 3(a) displays the cockpit of the vehicle. The measuring computer can be identified, which is attached to the passenger’s footwell using a holding device. In addition, the driver is equipped with a GoPro, which is not connected to the measuring computer and ROS. The purpose of the GoPro is to compare the measurement data with the cockpit display, if necessary. Fig. 3(b) shows the back seat, which contains the ADMA set-up (framed in red). To ensure the most rigid connection possible to the vehicle, the ADMA is screwed to a wooden plate connected to the seat and to the vehicle via

ITEM profiles on the floor. The mounting is further secured with a tension belt to avoid relative movements. The ADMA data are sent to the measuring computer via Ethernet. Fig. 3(c) and (d) show the boot of the vehicle. On the left side, c) a power supply unit can be seen, which is fed via the 12 V connection of the vehicle and provides up to 300 W of power for measuring equipment. Connected to this is the V2X receiver module from Commsignia [21] (d: right) and an antenna (d: left), which receives the vehicle’s CAM and forwards it to the measurement computer via Ethernet.

The technical data of the ADMA-G-PRO+ are given in Table 2. The

Table 2

Technical data of the ADAM-G-PRO+.

ADMA-G-PRO+	Measurement Range	Measurement Accuracy
Position	/	0.01 m – 1.5 m
Acceleration	$\pm 49 \text{ m/s}^2$	$< 0.01 \text{ m/s}^2$
Heading	$\pm 180^\circ$	0.01°

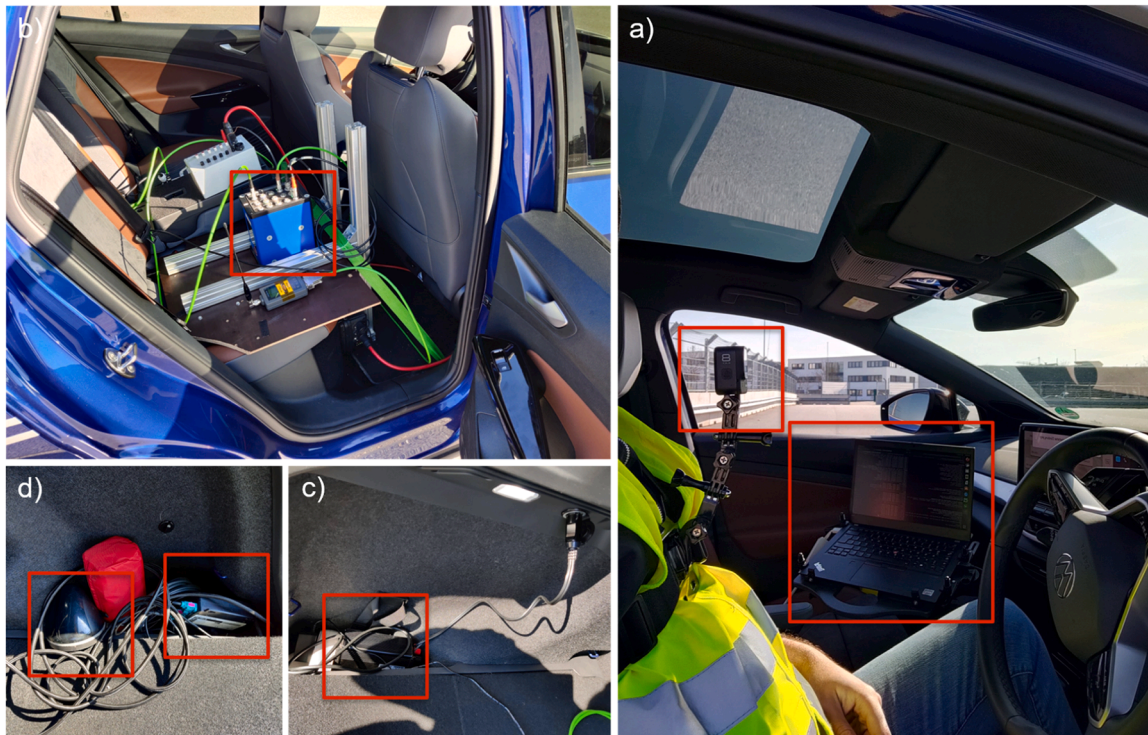


Fig. 3. Experimental set-up using the VW ID.4 as an example; (a) Cockpit with GoPro and measuring computer (b) Rear seat with installed ADMA (framed in red); (c) Boot left with power supply module for V2X module; (d) Boot with antenna (left) and V2X module (right) framed in red.

position accuracy depends on the DGNSS correction data and can vary between 1 cm and 1.5 m [22]. During the measurements at the CAR-SSMA outdoor site, correction data were always available, which is why a position accuracy of 1 cm was achieved. Accelerations can be measured up to 49 m/s^2 (5 g) with an accuracy of less than 0.01 m/s^2 . The orientation of the vehicle is measured with an accuracy of 0.01° . All other parameters are derived from this in the ADMA.

2.2.2. Testing area

Measurements with the described test set-up were carried out on the CARISSMA test site in the east of Ingolstadt. Fig. 4 is a top view of the CARISSMA test site. This can be divided into two parts a) high dynamic area and b) curving area. Experiments with high longitudinal dynamics are carried out in area a). Experiments with lateral dynamics are carried out in area b), which can be seen in Fig. 4(c) based on the experimental set-up for the curves.

No large buildings or other disturbing elements around the site could negatively affect the GPS signal and, thus, the achievable accuracy. The tests were all carried out in clear and dry weather conditions.

2.3. Experimental design

The methodical execution of the tests is based on the four trigger conditions, which should be addressed as independently as possible to examine the trigger and the associated generation frequency of the CAMs, as well as the quality of the message data under different dynamic conditions. Each of the described tests was carried out three times to generate minimum statistics for the evaluation. An overview of all the tests carried out can be found in Table 3.

2.3.1. Trigger ΔT_{Time}

As described in Section 2.1.1, CAMs are sent at 100 ms intervals because the trigger conditions are only checked every 100 ms. The message is sent time triggered if no trigger condition is activated within 1000 ms. Trials with time trigger were carried out with the vehicle stationary. In particular, the accuracy of the position and heading data were determined, which can be used as a reference for the accuracy of the data under dynamic conditions.

2.3.2. Trigger $\Delta V_{\text{Velocity}}$

The speed change trigger specifically describes an acceleration, as the algorithm checks the change in speed over time. To investigate this trigger, acceleration and deceleration tests are carried out in the outdoor area, as shown in Table 3. Maximum acceleration and deceleration are always performed, as this is reproducible and can be done without test subjects. The aim is to show what maximum can be achieved with the

Table 3
Overview of the conducted tests.

Trigger	Experiment	Description	
ΔT_{Time}	Standing	/	
$\Delta V_{\text{Velocity}}$	Max. Acceleration	0 – 30 km/h, 30 – 50 km/h	
		0 – 50 $\frac{\text{km}}{\text{h}}$, 50 – 80 km/h	
	Max. Deceleration	0 – 80 km/h	
		0 – 100 km/h	
		30 – 0 km/h	
$\Delta P_{\text{Position}}$	Const. Velocity	50 – 0 km/h	
		80 – 0 km/h	
		100 – 0 km/h	
		130 – 0 km/h	
		150 – 0 km/h	
$\Delta H_{\text{Heading}}$	Curve ($r = 6 \text{ m}$)	30, 50, 80, 100, 130 and 150 km/h	
		Curve ($r = 12 \text{ m}$)	7, 15 and 30 km/h
		Curve ($r = 20 \text{ m}$)	7, 15 and 30 km/h
		15, 30 and 60 km/h	

data in terms of generation frequency and accuracy and whether there is an acceleration dependency on the accuracy of the data. The experiments thus cover the outer limits of the space of interest. Typically, in accident analysis, the acceleration behavior of the normal driver is of great importance. This is, therefore, in the area of interest and should have even higher accuracies.

2.3.3. Trigger $\Delta P_{\text{Position}}$

To respond to this trigger, tests are carried out at constant speeds of 30 to 150 km/h (see Table 3). To achieve a constant speed, the vehicles' Adaptive Cruise Control (ACC) system was used. Due to space restrictions in the testing area, only tests up to 80 km/h could be carried out there. For the higher speeds, test drives were done on the nearby highway A9. Due to correction data available throughout Bavaria via the cellular network, ADMA was also able to generate highly accurate reference data there. Besides the accuracy, the speed dependency of the accuracy is investigated with these tests, as well as the occurred generation frequency.

2.3.4. Trigger $\Delta H_{\text{Heading}}$

Similar to the trigger position change tests, these tests were run at a constant vehicle speed using the ACC System (see Table 3), whereby three different curve radii (6 m, 12 m, and 20 m) were driven to generate defined yaw rates. Again, the generation frequencies occurring and the parameters' accuracies are to be determined as a function of the yaw rate. Fig. 4(c) shows the test set-up for the 6 m and 12 m curves on the outdoor site. The set-up of the 20 m curve is analogous.

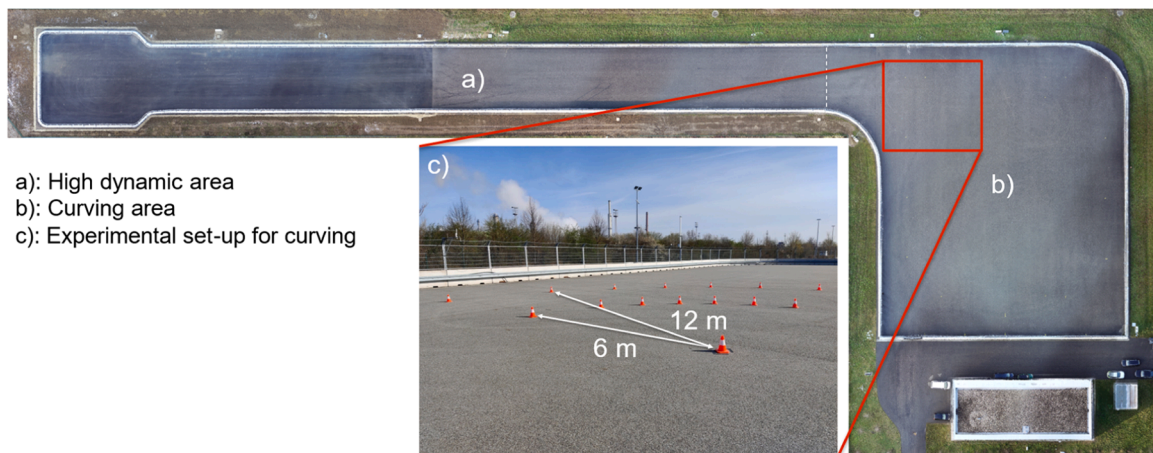


Fig. 4. Representation of the test environment; (a) and (b) outdoor test site of CARISSMA in Ingolstadt; (c) test set-up for cornering with radius 6 m and 12 m.

2.4. Evaluation methods

The procedure in Fig. 5 is executed to evaluate the data. The timestamped data are first filtered to extract the relevant part of the measurement values for the analysis. For example, the data at the beginning and end of the measurement are cut off for the constant runs to not consider the acceleration to the target speed and the braking process towards the end of the test in the evaluation. After filtering, the reference data are time-synchronized with the CAM data. This is explained in more detail in the following Section 2.4.1. When comparing data, the approach to determine the position error is of particular interest. This is explained in more detail in Section 2.4.2. Finally, the method for statistical evaluation is presented in section 2.4.3.

2.4.1. Method for measurement data synchronization

When determining the accuracy of the measured data sets by comparing it with a reference system (ADMA), two key points need to be considered. Firstly, the test vehicle and the measurement environment must have the same time base (GPS time, UTC time) to avoid a systematic error due to different local clocks. Secondly, both data sets must be compared within the time base at the same point. Due to the discretization of the measurement data by the sampling rate, a time offset is also possible.

Fig. 6 illustrates how both key points were solved in the present work. It can be seen that both the V2X vehicle and the ADMA rely on GPS time, which leads to sufficient sub-millisecond time synchronization between the comparing systems [23]. In principle, time synchronization could be improved by using a local time server or additional GNSS correction signals. However, this was not applicable in this work, as accessing the V2X modules of the series vehicles was impossible.

From using real V2X vehicles arises another problem: the CAM data received in the ROS environment do not directly contain the GPS timestamp indicating when the data for generating the CAM were extracted from the vehicle. On the other hand, the UTC timestamp of ROS still contains the latency between data generation and publication of the data in ROS. According to [24], this latency corresponds to the communication delay and the processing time within the Commsignia module until publishing in ROS, illustrated by the arrows in Fig. 6. As the ROS environment uses UTC, which is synchronized via the Internet-based time servers, there is an additional time deviation due to using two different time bases, which we refer to as time base error. With the help of the parameter *GenerationDeltaTime* ($Gen\Delta t$) [3], the latency can be calculated, as it contains the GPS time at which the data were generated in the vehicle. However, this parameter does not directly contain the generation timestamp, but the mode of 2^{16} of the time difference since 2004-01-01T:00:00:00Z in milliseconds [3]. The resulting residual value indicates the message age.

To determine the latency from CAM generation to reception in ROS, the *ReceivedDeltaTime* with the UTC timestamp attached to the CAM by ROS ($Rec\Delta t_{ROS}$) must be calculated and subtracted from the CAM *GenerationDeltaTime* ($Gen\Delta t_{CAM}$).

$$Rec\Delta t_{ROS} = (tStamp_{UTC,CAM} - RefTime_{2004})ms \bmod 2^{16} \quad (2.1)$$

$$\text{if } Rec\Delta t_{ROS} \geq Gen\Delta t_{CAM} \rightarrow \text{latency} = Rec\Delta t_{ROS} - Gen\Delta t_{CAM}$$

$$\text{if } Rec\Delta t_{ROS} < Gen\Delta t_{CAM} \rightarrow \text{latency} = 2^{16} - Rec\Delta t_{ROS} + Gen\Delta t_{CAM} \quad (2.2)$$

The time base error due to the use of the CAM ROS UTC timestamp is also included in the calculated latency time. By subtracting the latency

from the CAM ROS UTC timestamp ($tStamp_{UTC,CAM}$), the GPS timestamp at the time of data generation in the vehicle is obtained ($tStamp_{GPS,corr}$), which was used in this work for the measurement data synchronization of the ADMA values according to Eq. (2.4).

$$tStamp_{GPS,corr} = tStamp_{UTC,CAM} - \text{latency} \quad (2.3)$$

Subsequently, the reference data of the ADMA must be temporally assigned to the received CAMs. Due to the sampling rate of 100 Hz, there is a maximum time deviation of 5 ms between the CAM and the reference data of the ADMA. At a speed of 150 km/h, this still corresponds to a local error of 0.2 m. For data synchronization, the dataset of the ADMA and its corresponding GPS timestamp ($tStamp$), which are recorded shortly before ($t-1$) and after ($t+1$) the generation of a CAM at time t , are used for a linear interpolation:

$$ADMA_t = \frac{ADMA_{t+1} - ADMA_{t-1}}{(tStamp_{t+1}) - (tStamp_{t-1})} \cdot (tStamp_{GPS,corr,t} - tStamp_{t-1}) + ADMA_{t-1} \quad (2.4)$$

By deducting the latency time from the CAM UTC timestamp, it was possible to determine the GPS timestamp when the CAM data was generated in the vehicle. The linear interpolation of the ADMA data to this point in time also minimized the error caused by the sampling.

2.4.2. Method for calculating position accuracy

To determine the accuracy of the transmitted position information, the distance of the ADMA's reference point to the CAM's reference point must be determined. According to [3], the transmitted position information of the CAM corresponds to the center of the front edge of the bounding box around the vehicle, shown in Fig. 7 using the example of ID.4.

The reference point of the CAM is thus a point of interest (POI_{CAM}), which can be directly considered in the measurement by the ADMA by specifying the distances starting from the coordinate system of the ADMA to the respective POI in the configuration menu.

The X- and Y-distance measurements were done manually with different measuring devices (laser measuring device and meter stick). The Y-distance of 280 mm to the vehicle's middle axis (MA) could be determined with a maximum deviation of 1 mm (reading inaccuracy) due to the small distance and direct measuring path. The measurement of the X-distance is more difficult, as this could not be measured directly through the vehicle to the front. The installation position of the ADMA in the X-direction was, therefore, projected outwards on a panel next to the car to measure the X-distance against another panel, representing the edge of the bounding box at the front. To eliminate inaccuracies in the projections and readings, the X-distance was determined three times in this way. This results in an average X-distance of 2993 mm, whereby a deviation of up to 5 mm can be assumed due to the scattering of the three measurements. Thus, together with the measurement deviations of the ADMA, there is a possible error of ± 1.5 cm for the measurement of the X-coordinate and ± 1.1 cm for the Y-coordinate. Since the transmitted position information is sent in longitudinal and latitudinal coordinates, the position difference must still be transformed into the vehicle's local coordinate system.

The difference between the longitudinal and lateral coordinates can be calculated from the measurement data.

$$\Delta lat = lat_{CAM} - lat_{ADMA} \quad (2.5)$$

and



Fig. 5. Schematic procedure for post-processing the data.

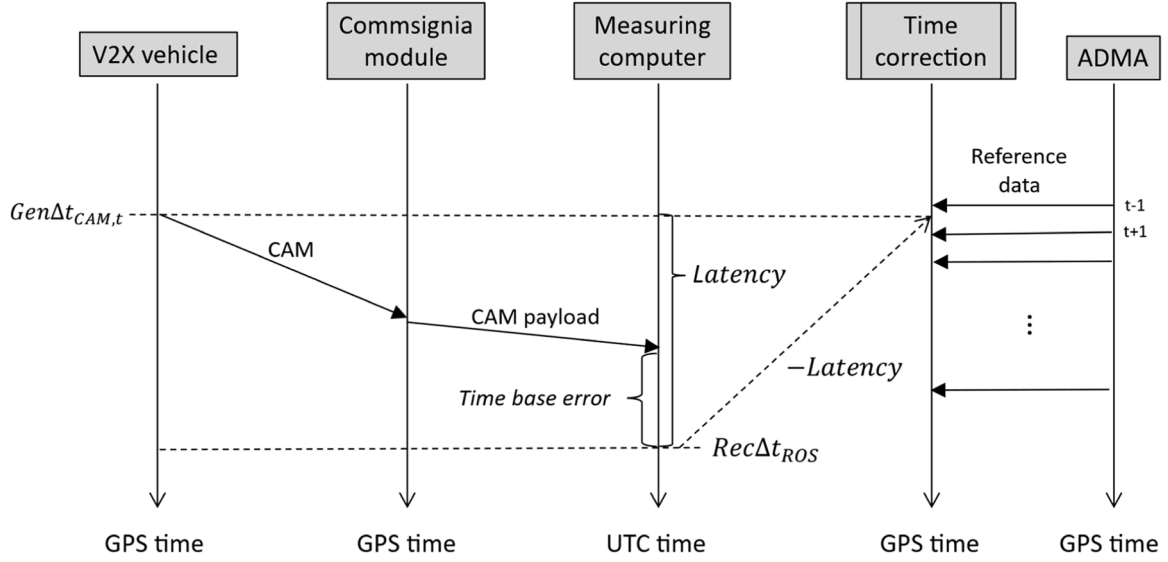


Fig. 6. Sequence diagram from the generation of the cooperative awareness message in the test vehicle until synchronization with the reference data.

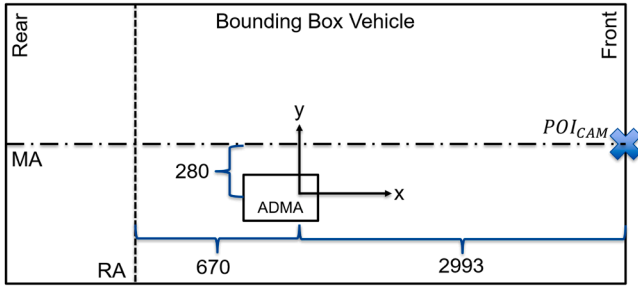


Fig. 7. Non-scale representation of the distances of the point of interest (POI CAM) to the reference point of the ADMA (origin coordinate system) using the example of the ID 4 (all data in mm).

$$\Delta long = long_{CAM} - long_{ADMA} \quad (2.6)$$

Then, according to [25], the Δx and Δy distance in the global coordinate ($\vec{e}_x = \vec{e}_{long}$, $\vec{e}_y = \vec{e}_{lat}$) can be calculated by:

$$\Delta x_{global} = 111300 \cdot \cos(lat_{ADMA}) \cdot \Delta long \quad (2.7)$$

and

$$\Delta y_{global} = 111300 \cdot \Delta lat \quad (2.8)$$

The rotation of the global coordinate system (GCS) into the local coordinate system (LCS) of the vehicle can finally be realized via the vehicle's heading using a passive rotation matrix [26]. The heading of the ADMA describes the angle ψ between the north vector and the X-axis of the vehicle in a mathematically positive direction [22]. This leads to the fact that with a heading of 0° , the local X-axis of the vehicle is on the global Y-axis. Therefore, to calculate the distances in the local vehicle coordinate system, the GCS must first be rotated by 90° in a mathematically positive direction. Then, it can be further mathematically positively transformed by the angle ψ into the LCS. This results in the following relationship for the rotation:

$$\begin{pmatrix} \Delta x_{local} \\ \Delta y_{local} \end{pmatrix} = \begin{pmatrix} \cos(90^\circ + \psi) & \sin(90^\circ + \psi) \\ -\sin(90^\circ + \psi) & \cos(90^\circ + \psi) \end{pmatrix} \cdot \begin{pmatrix} \Delta x_{global} \\ \Delta y_{global} \end{pmatrix} \quad (2.9)$$

2.4.3. Statistical evaluation method

Accuracy, which is the subject of this study, is "the closeness of agreement between a test result and the accepted reference value" [27].

The accepted reference values are determined by the ADMA's highly accurate reference measurement system. The test results represent the values in the CAM message.

To evaluate the accuracy $Accy$ of the message content of the CAM, the absolute difference values dY_i between the CAM and ADMA data are formed for the different investigation parameters Y_i .

$$Accy(Y_i) = dY_i = CAM_{Y_i} - ADMA_{Y_i} \quad (2.10)$$

The difference dY_i is also called absolute error in this work. Subsequently, the statistical distribution of the accuracy is described descriptively using boxplot diagrams. An inductive analysis of the accuracy of the population of all vehicles, on the other hand, is not possible because different manufacturers would act as an independent variable. However, since all test vehicles in the present study are from a single manufacturer and no V2X-capable vehicles from other manufacturers are yet commercially available in the EU market, this cannot be verified. The applicability of the results to the full population thus requires continuing the study as soon as more V2X-capable vehicles from other manufacturers are available.

It is also useful to consider the relative accuracy to better classify the results. For the calculation of the relative accuracy $relAcc$, the following equation results for the different investigation parameters Y_i :

$$rel\ Accy(Y_i) = \frac{X_i - dY_i}{X_i} \quad (2.11)$$

where X_i describes the reference value of the parameter and dY_i the current absolute error from the reference value at time i .

For the reference variable X_i the following is chosen for the CAM parameters under investigation:

- Velocity: value of the velocity at time i ,
- Longitudinal acceleration: value of the longitudinal acceleration at time i ,
- Longitudinal position: vehicle length,
- Lateral position: vehicle width,
- Heading: 360°
- Yaw rate: value of the yaw rate at time i .

Eq. (2.11) thus gives a value of 100% when the accuracy is 100%, and consequently, the relative error is zero.

3. Results and discussion

3.1. Standing vehicle tests

Fig. 8 shows the results of the standing tests with the test vehicles as a boxplot diagram. Measurements were carried out at three different points on the CARISSMA site. The abscissa shows the investigated parameters. The ordinate shows the accuracy, with the values indicating the error.

The value zero means no error, and thus, the accuracy is maximum. The orange line in the boxplots indicates the median value. The green triangle shows the mean value. The position accuracy in the longitudinal (dx) and lateral direction (dy) of the vehicles, as well as the accuracy of the heading information ($dheading$), were evaluated. For the description and evaluation of the results, the median is mainly considered for all results, as it is more robust against outliers.

A very different picture of the results can be recognized. While the median positional accuracy of the ID.4 is still in the cm range, the error and scattering increase further over ID.3 towards Golf 8 with median error of approx. 1.6 m. The appearance of the boxplots for ID.3 and Golf 8 is also special, as the whiskers lie on the ends of the boxes. This shape results from the measurement data jumping back and forth between a few measurement values. The median accuracy of the heading is less than 0.5° for all vehicles, whereby the scattering is greatest in absolute terms compared to the other parameters. In relative terms, the heading error is small since an error of 1.6 m is much greater in relation to the vehicle dimensions than a heading error of 3° .

Overall, the decrease in accuracy towards the Golf 8 model is presumably due to different software versions. The Golf 8 is the first V2X-capable series vehicle model, i.e. represents the oldest implementation stage, followed by the ID.3 and ID.4. Therefore, it is plausible to assume that the accuracy of the information sent increases with the development of the vehicles and better software.

Fig. 9 shows the transmitted accuracy of the heading information in the CAM and the actual accuracy. It can be observed that the heading

information for the vehicle models ID.3 and ID.4 is more accurate than stated by the heading confidence parameter of the CAM. For the model Golf 8, it is the opposite, reflecting the lower accuracy of the Golf 8 compared to the other vehicles. In addition, it can be seen that the transmitted accuracy information of the Golf 8 is also the worst.

3.2. Full acceleration/deceleration tests

Before evaluating the maximum acceleration and deceleration tests, the measurement data were filtered to only consider the actual acceleration curve. Therefore, all measurement data with accelerations $< 0.2 \text{ m/s}^2$ in the full acceleration tests and $> -0.5 \text{ m/s}^2$ in the full deceleration tests were filtered out. These filters could be determined by visual inspection of the acceleration-time curves.

Fig. 10 illustrates the accuracy of the CAM parameters during the full acceleration tests as a boxplot diagram. In addition to the position and heading accuracy, the speed ($dvelocity$) and longitudinal acceleration accuracy (dq_{long}) were also evaluated. The yaw rate was not evaluated because the tests were only carried out in the longitudinal direction.

Again, the increasing accuracy towards the ID.4 can be seen, which on average shows very high accuracies ($dv = -1.43 \text{ km/h}$, $dq_{long} = 0.16 \text{ m/s}^2$, $dx = 1.8 \text{ m}$, $dy = 0.17 \text{ m}$, $dheading = 0.03^\circ$) with also very low scattering. The heading accuracy is similar for all vehicles and also shows a low scattering. The same applies to longitudinal acceleration.

Larger median errors occur for the speed information ($dvelocity_{ID.3} = -2.34 \text{ m/s}$, $dvelocity_{Golf8} = 5.16 \text{ m/s}$) as well as the longitudinal position ($dx_{ID.3} = -1.70 \text{ m}$, $dx_{Golf8} = 4.82 \text{ m}$) of the ID.3 and Golf 8. In addition, the scattering increases steadily over the ID.3 towards the Golf 8, which again shows the increase in accuracy over the vehicle development age. Across all vehicles and parameters, it can be noted that the median and mean values are very close to each other.

Regarding the requirements, ID.4 has a higher speed and position accuracy than required at maximum acceleration. On the other hand, the median speed accuracy of ID.3 and Golf 8 is below that of the EDR but for ID.3 better than stated in the literature when no EDR is present.

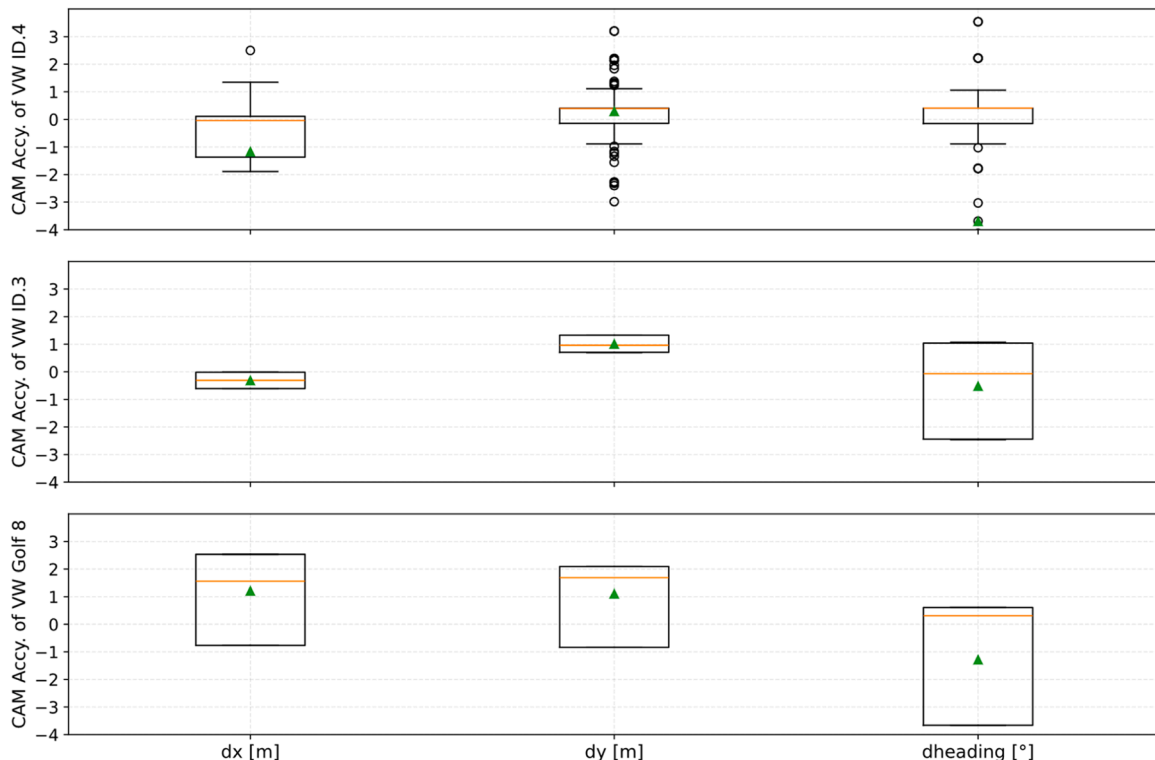


Fig. 8. Accuracy of the investigated CAM parameters in the standing tests illustrated as boxplot diagrams.

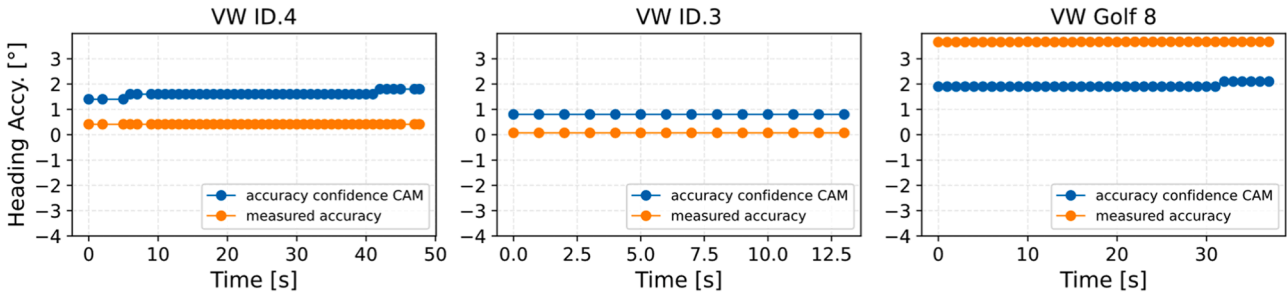


Fig. 9. Comparison of transmitted Heading Confidence in CAM with actual accuracy in standing position.

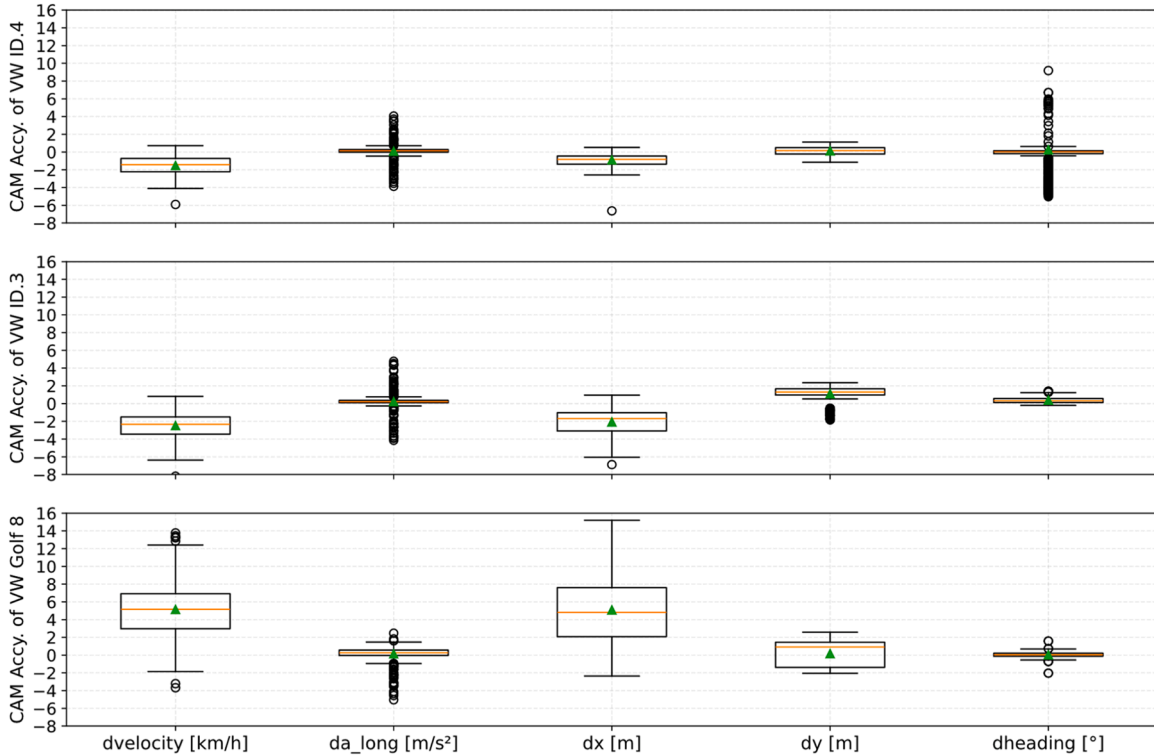


Fig. 10. Accuracy of the parameters investigated at full acceleration over all tests.

The median longitudinal position accuracy of the Golf 8 is outside the required accuracy of 1 to 2 m of the safety applications. The ID.3, on the other hand, at least meets the 2 m requirement of the ICRW application. The median lateral position accuracy of both vehicles also meets the 2 m requirement of the ICRW application. Overall, it can be stated that at full acceleration, a high level of accuracy already prevails, which fulfils the requirements of V2X and accident analysis for the newer models.

A similar picture can be detected in the results of the accuracies for the full deceleration tests in Fig. 11. Compared to the accuracies for the full accelerations, the speed accuracy of the CAM values for all vehicles decreases due to the higher acceleration values for the full deceleration. In addition, the scattering increases noticeably. On the other hand, the median longitudinal acceleration accuracy remains at a similarly good level, although the scattering also increases. In contrast, the median error of the heading and its scattering remain unaffected. Although significantly higher acceleration values occur for full deceleration compared to full acceleration, the median position accuracy of the vehicles only deteriorates minimally. This shows that the greatest influence of acceleration is on the accuracy of the speed information of the CAM. Again, the median and mean are very close to each other.

Due to the high accelerations, the speed accuracy of the ID.4 falls below the required 1 km/h of the EDR. However, it is also doubtful that

the EDR meets the requirement in the standard itself with a full deceleration. Due to the lack of publications on this topic, this cannot be analyzed further. Nevertheless, the median error of 4.19 km/h is still better than the accuracy of classic accident reconstruction without EDR. The ID.3 is just above this requirement at 5.39 km/h. Golf 8 has the largest median error, with -17.1 km/h. The ID.4 still achieves the 2 m of the ICRW for the accuracy of the longitudinal position. The ID.3 and Golf 8 both exceed this requirement. With regard to the lateral position, the ID.4 also fulfils the 1 m of the LCRW. The ID.3 and Golf 8 fulfil at least the 2 m of the ICRW application.

As with the stationary tests, the accuracy information of the heading value sent along was evaluated to investigate the influence of acceleration on the accuracy information sent. The accuracy information provided by the vehicle is always more conservative than the actual accuracy. The heading accuracy is thus at least as accurate as indicated and sent by the vehicle at high accelerations. Whether this is the case for all parameters, especially for the transmitted speed and acceleration accuracy, cannot be evaluated due to the lack of data.

Fig. 12 shows the parameters' accuracy as a function of acceleration. The dependence of the speed information on the acceleration can be observed in particular for Golf 8 and decreases over ID.3 to ID.4. This corresponds well with the previous findings. On the other hand, the

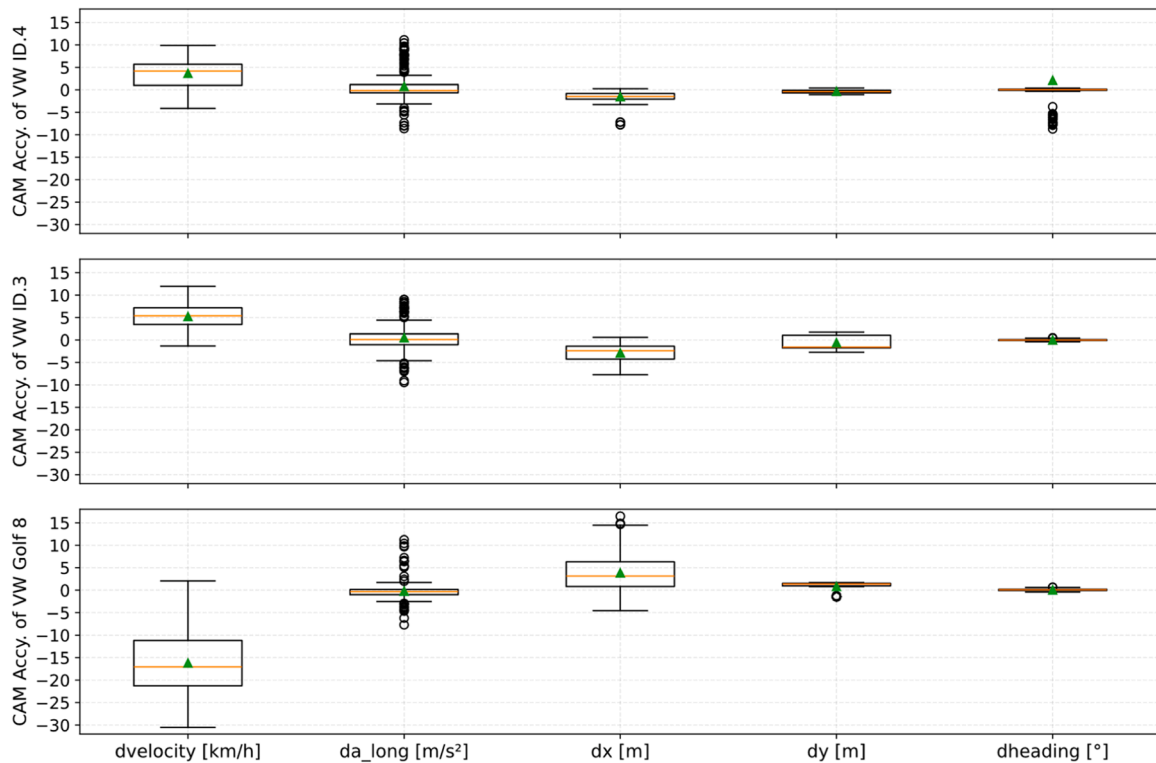


Fig. 11. Accuracy of the parameters investigated at full deceleration over all tests.

accuracy of the longitudinal information of the CAM shows no dependence on the acceleration itself. The other parameters also show no dependencies on acceleration. The same findings can be found for the dependence of the parameters on the acceleration during a full deceleration, which is illustrated in Fig. 18 in the appendix.

Finally, the generation frequencies that occurred are briefly described to determine the expected value for this at full acceleration and deceleration. This is especially important to show the resolution compared to EDR in the pre-crash phase, which stores data with 2 Hz.

Considering the predominant generation frequencies during the tests for full acceleration from a standstill, a similar picture can be recognized for all vehicles. Although the percentage distribution differs between the vehicles, which is due to the respective power-to-weight ratio and thus acceleration capacity, it can be noted that the acceleration test from 0 to 30 km/h has a relatively high proportion of 5 Hz generation frequency since at the beginning of the measurement the acceleration is not yet fully built up and therefore lower proportions than 10 Hz generation frequency occur. At 0 to 50 km/h, a generation frequency of 10 Hz is already dominant since the acceleration is fully built up over the entire duration. As shown in [28], the acceleration capacity of electric vehicles decreases starting from 50 km/h, which is why the proportion of 5 Hz generation frequency increases steadily during accelerations to higher speeds. The situation is different for the generation frequencies that occur during full deceleration. There, 10 Hz is the predominant generation frequency independent of the starting speed. The occurrence of lower generation frequencies is due to the border areas of the considered measurement data, which show lower accelerations and, thus, generation frequencies. Another reason could be the loss of some data packets during transmission. The resulting generation frequencies are illustrated in the appendix in Figs. 19 and 20.

3.3. Constant velocity tests

Before evaluating the constant speed runs, the measurement data were filtered to only consider the portions of the measurement data with

the constant target speed. Therefore, all measurement data with accelerations ($< -0.04 \text{ m/s}^2$ and $> 0.04 \text{ m/s}^2$, as well as speeds ($< 20 \text{ km/h}$ or $> 160 \text{ km/h}$), were filtered out of the test data for the constant-speed runs. These filters could be determined by visual inspection of the time curves.

Fig. 13 presents the determined accuracies of the CAM parameters during the tests with different constant speeds from 30 km/h to 150 km/h as a boxplot diagram. The position and heading accuracy, as well as the speed accuracy, were considered. The yaw rate and longitudinal acceleration were not evaluated because the tests were carried out on a straight track, and no accelerations were to be evaluated at a constant speed. A high median accuracy of all test parameters can be recognized for all three test objects. In particular, the speed accuracy for all vehicles is, on average less than 1 km/h with a very low scattering. The same applies to the accuracy of the heading information sent. The longitudinal position shows the lowest accuracy and greatest scattering, which is greater than in the acceleration tests. The median lateral position accuracy is also below 1 m for all vehicles.

Thus, all vehicles have a higher median speed accuracy than required by the EDR. The median lateral position accuracy is also less than 1 m for all vehicles. Only the median longitudinal position accuracy, which is greater than 2 m for ID.4 and Golf 8, is not sufficient for the safety applications. As with the acceleration tests, the medians and mean values are very close to each other.

Fig. 14 shows the dependence of the accuracy of the study parameters on the speed as a boxplot diagram. A direct dependence on speed can only be seen for the accuracy of the longitudinal position across all vehicles. On the other hand, the lateral position accuracy shows a greater fluctuation, which decreases with higher speeds. Regarding speed accuracy, only the Golf 8 has a small decrease in accuracy at high speeds. However, this disappears with the newer models. As can be seen from the previous figures, heading accuracy is not influenced by speed. Therefore, dependence on speed can only be identified for the longitudinal position accuracy.

The sent heading accuracy shows the same picture as for the acceleration tests. All vehicles estimate the accuracy worse than it is. It is

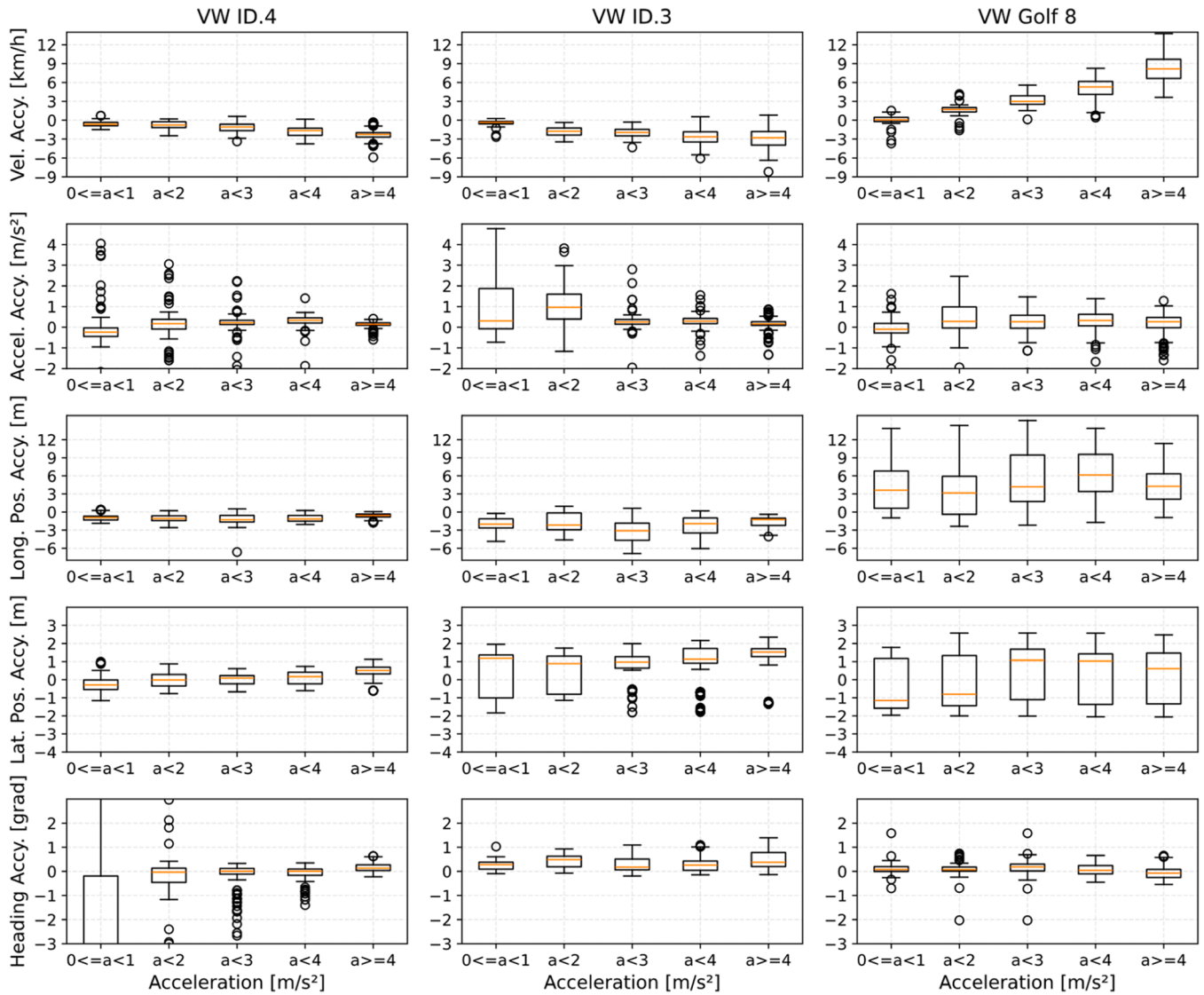


Fig. 12. Examination parameters are shown via acceleration at full acceleration.

already evident here that there is no speed dependency on the accuracy of the heading information. In addition, the heading information sent is extremely accurate at a constant speed, as it is always close to 0° error. Thus, the vehicles estimate the accuracy more conservatively again than they are.

Finally, the generation frequencies are analyzed and illustrated in Fig. 21 (see appendix). Since no change in heading or acceleration occurred during the tests, the triggering of the message is solely dependent on the speed trigger. At a speed of 30 km/h, a generation frequency of theoretically 2 Hz results according to the standard. However, the generation frequency of 1.66 Hz was the most frequent at a speed of 30 km/h. This is because the tests were carried out according to the indicated speed of the tachometer, and the actual speed was approx. 3 km/h less. Since 27 km/h is below the threshold value of 2 Hz, the CAM is only transmitted with 1.66 Hz. Other reasons for the deviations from the expected frequency could also be the fluctuations of the generation frequency determined in [9]. It can be seen here that the fluctuations in the generation frequencies are greatest for the Golf 8 and smallest for the ID.4. From 80 km/h up to 130 km/h, 5 Hz should be the predominant generation frequency, which is also the case for most of the tests. Larger errors can be seen at 130 km/h for Golf 8 and ID.3, which already send a large proportion of messages at 10 Hz. At a speed of 150 km/h, all messages should be sent with 10 Hz, which is clearly reflected

in the results. It can thus be stated that the generation frequency depends on the ground speed and is not triggered by the indicated speed. The generation frequencies then correspond to the expected value at higher velocities.

3.4. Curve driving tests

The data were also filtered to only consider the measurement data during the drive through the curve for the evaluation. This was done by considering data with a transverse acceleration of at least 0.05 m/s^2 . In addition, all data whose heading information was not in the range between 213° and 300° were filtered out. These filters could be determined by visual inspection of the time curves.

Fig. 15 illustrates the determined accuracies of the CAM parameters over all cornering tests at different curve radii and speeds as a boxplot diagram. The position and heading accuracy, as well as the speed and yaw rate accuracy, were investigated. The longitudinal acceleration was not evaluated, as the cornering was driven at a constant speed.

The median accuracy of the speed is less than 1 km/h for all vehicles and has a small scattering. The same applies to the longitudinal position, whereby the scattering of the parameters is greater than the speed scattering. The accuracy of the lateral position shows median errors of up to 1.64 m, which is not a significant deterioration compared to the

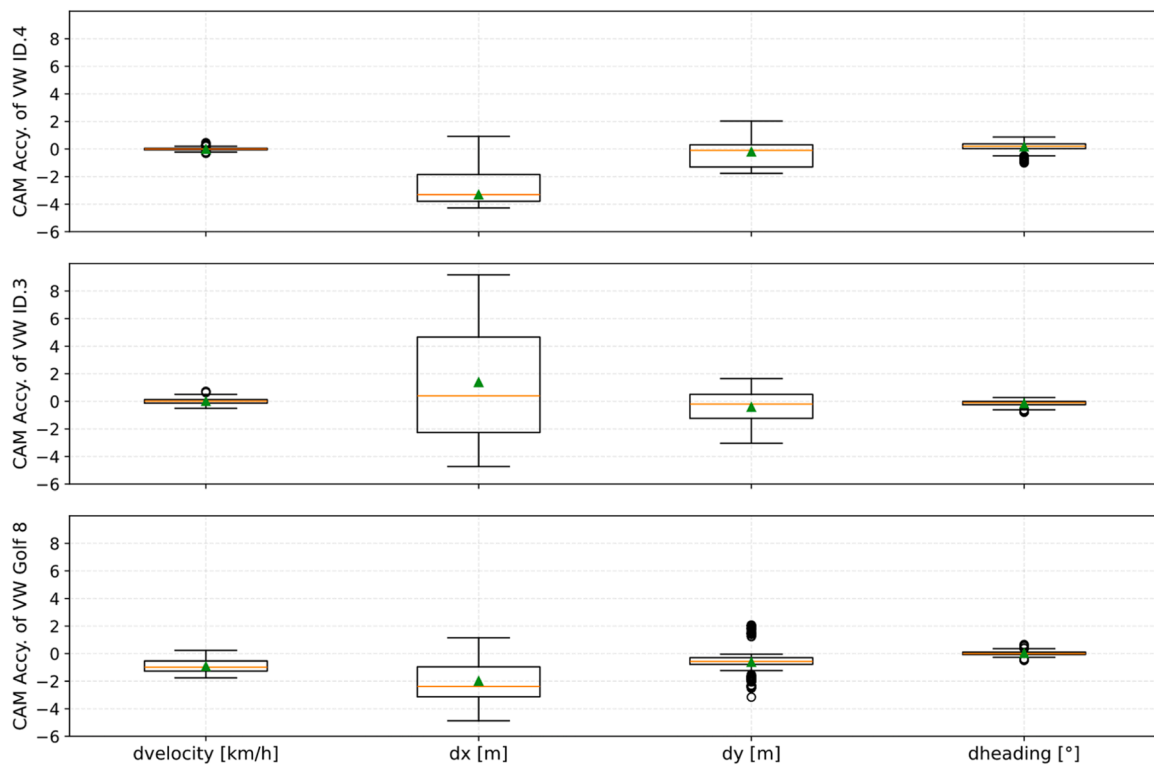


Fig. 13. Accuracy of the parameters investigated while constant driving over all tests.

previous test series. Only the scattering is slightly larger. Large differences compared to the previous test series can be seen in the accuracy of the heading. While the accuracy of the heading was always close to zero in the previous tests, greater errors of up to 3.68° now occur with ID.4. In addition, the increase in the scattering of the values across all vehicles is significant. The median of the accuracy of the yaw rate, on the other hand, shows a high accuracy close to zero. However, this parameter is also subject to a larger scattering. Unlike in the previous tests, there is no significant difference in the median accuracies and scattering between the vehicles. Thus, the accuracy and the scattering of the parameters during cornering are, to a certain extent, independent of the vehicle. The deviation of medians and mean values is slightly larger in the curve tests than in the other test series. Nevertheless, they are still close to each other.

Regarding the requirements, it can be observed that both the speed and longitudinal position accuracy, on average, meet the EDR and LCRW application requirements. The median lateral position accuracy also meets the ICWR application requirements for all vehicle models under evaluation, however since the lateral accuracy is over 1 m for both the ID.4 and Golf 8, this parameter does not fulfill the LCRW requirements for these two vehicle models. As a result, only the ID.3 meets all requirements here.

Fig. 16 shows the dependency of the parameters on the yaw rate. It can be stated that more parameters than before depend on the yaw rate. Thus, a decrease in accuracy over an increasing yaw rate can be observed for speed and heading. For high yaw rates, the median error for speed increases to about 2 km/h across all vehicles. The strongest dependency, however, is shown by the heading accuracy, which increases to a median error of almost $6\text{--}9^\circ$ for all vehicles.

A decrease in accuracy is consequently also evident for the yaw rate information, whereby the median accuracy only shows a small absolute error of approximately $2\text{--}3^\circ/\text{s}$. However, the scattering increases strongly with a rising yaw rate. Larger differences between the vehicles regarding the yaw rate dependence on the accuracy of the information are not evident.

Fig. 17 compares the sent information accuracy of the heading in the CAM with the measured accuracy in the curve driving tests with a radius of 6 m. The graphs are similar for all tests and vehicles. While in the tests with lower curve speeds and thus yaw rates, the vehicle still underestimates the accuracy, it is overestimated at high yaw rates. Also, the indicated accuracy increases with higher speed, although the actual accuracy decreases. The same result is also observed in the curve driving tests with larger curve radii, why this is not explicitly shown here.

Finally, the occurring message frequencies are examined again. In the tests for cornering with a curve radius of 6 m and a speed of 7 km/h, a large scattering of the generation frequencies was found. Based on ideal cornering, a generation frequency of 3.33 Hz is expected in this test series. Even if this is one of the most frequent frequencies, many lower frequencies occurred while testing. The lower generation frequencies are due to deviations during the test. These occurred because of the difficulty of driving at a constant speed of 7 km/h since the cruise control of the vehicles can only be used at speeds of 30 km/h and higher. In addition, the speedometer's indicated speed was also used here, why the vehicle was slower in reality. In addition, there are deviations in the actual curve radius driven due to the test set-up (pylons mark the inner radius of the trajectory) and the test execution (no ideal circular drive by the driver). This leads to increased scattering of the generation frequencies, especially in the tests at 7 km/h. The tests with higher speeds show that the scattering decreases due to the deviations caused by the test set-up and the test execution and that the expected generation frequency (15 km/h = 5 Hz and 30 km/h = 10 Hz) appears to be dominant. The same observations apply to the results of the other tests with larger curve radii. Just the tests with a speed of 60 km/h are an exception. Here, the expected generation frequency is 10 Hz. However, the most frequently occurring generation frequency is 5 Hz. A possible explanation for the lower generation frequency could be the Electronic Stability Control (ESC) System, because at these speeds, the ESC intervened in a regulating manner during the tests and an increased slip between the tire and the road occurred. All results are illustrated in Figs. 22–24 in the appendix.

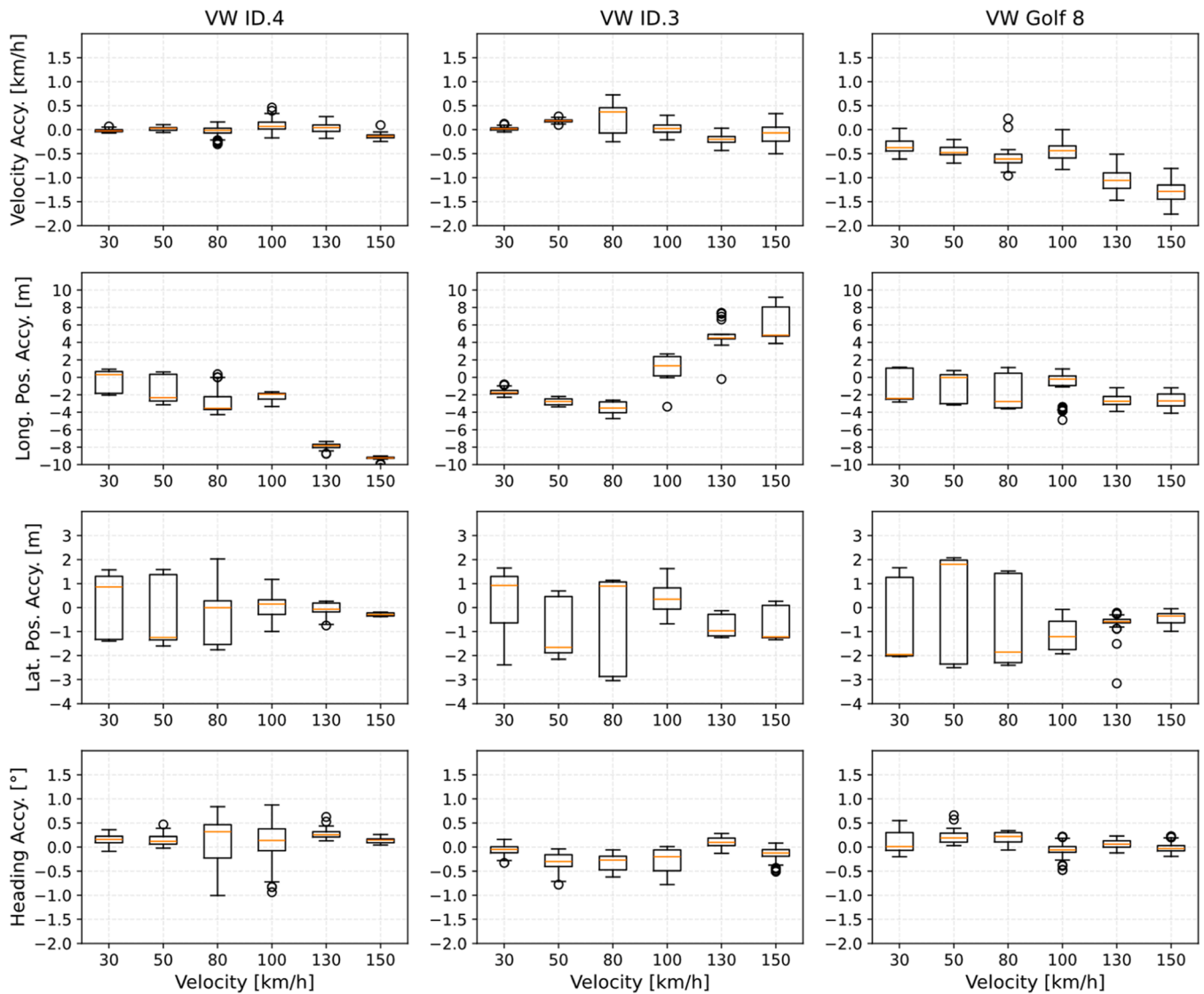


Fig. 14. Examination parameters are shown via velocity during constant driving.

3.5. Summary of results

Table 4 summarizes the results of the tests. For this purpose, the median, mean, median absolute deviation (MAD) and standard deviation (SD) of all test series and parameters were calculated. Confidence intervals can be calculated using the mean and standard deviation. For a better interpretation of the results, the median and MAD are also given, as these are more robust against the frequently occurring outliers. Thus, it can be estimated how trustworthy the calculated confidence interval is.

In [29], there is also a possibility described to determine a confidence interval with median and MAD. Due to the different amounts of measurement data per test and vehicle, it was impossible to calculate the statistic parameters directly with the data of all test vehicles, as the vehicle with the most collected data per test has a stronger influence on the result. Instead, the mean values of the statistical parameters were calculated for the three test vehicles for each test and parameter. In addition, the absolute values were used for the mean value calculation that high positive and negative errors do not result in zero again on average. However, the direction of the error is lost through this consideration. The curve driving tests were also summarized in the table over all curve radii.

Table 5 lists, analogous to Table 4, the relative accuracy of the test

parameters according to Eq. (2.11). The median and mean values of the relative accuracies were calculated. With one exception, the mean value of the relative accuracy is always smaller than the median. This shows the influence of outliers on the results. Thus, for the discussion of the results, the median is again primarily referred to.

A decrease in accuracy towards increasing accelerations can be detected for the absolute and relative accuracy of speed. At constant speed and driving in curves at a constant speed, the relative velocity accuracy is close to 100%. The median error for all test series is, thus, smaller than given in the literature from section 2.1.2 for speed. In addition, the accuracy of the speed, except for the acceleration tests, is below 1 km/h, as required in UNECE R160 for the EDR. Even with an accelerating vehicle, the errors are smaller than the accident reconstruction error without EDR Information. This is not the case at high decelerations, as seen in the example of ID.3 and Golf 8 in section 3.2. Nevertheless, it can be stated that the speed information would greatly improve the reconstruction accuracy of the vehicle speed in the pre-crash phase. That such a high accuracy of the speed information is generally achieved could already be guessed from the specifications of the EDR. Thus, the data source for the data in the EDR and the CAM is most likely the velocity information on the CAN bus, which is why similar accuracies were to be expected. This could be confirmed in this work.

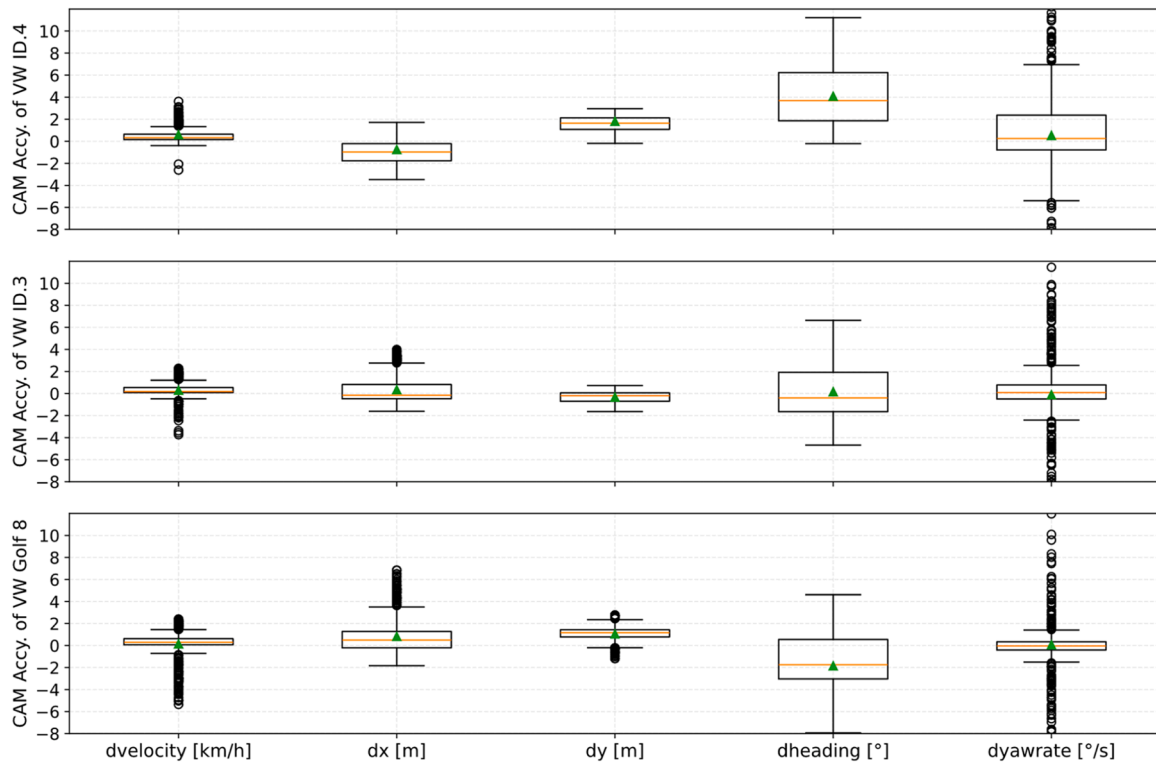


Fig. 15. Accuracy of the parameters investigated at curve driving over all tests ($r = 6$ m, $r = 12$ m and $r = 20$ m).

On the other hand, the position data of the CAM have greater relative errors. This inaccuracy results from the limitation of accuracy on the part of GPS. It could be expected before that the accuracy would equal the GPS accuracy if Volkswagen did not install a dGPS. The results show that Volkswagen implements localization without dGPS, which may be too low to meet the accuracy requirements of safety-relevant applications. It would be advisable to further increase the accuracy to implement future applications safely. In addition, the relative accuracy here is related to the vehicle dimensions, which is why the percentage accuracy indicates the proportion of overlapping areas of the bounding boxes of the vehicles between the reference and CAM. For example, an accuracy of 50% means that 50% of the area of the vehicles overlaps. This is just achieved in the longitudinal direction for standing and curve driving tests. On the other hand, the lateral position error is between 1/3 and 2/3 of the vehicle width. Concerning the requirements of the LCRW and ICRW applications, it can be stated that the median lateral position accuracy is almost sufficient for both, whereby the required accuracy of 1 m is slightly exceeded at high decelerations, fast cornering, and while standing. The median accuracy of the longitudinal position, on the other hand, only meets the requirement of 1 m when standing and cornering. The median accuracy for the other tests is above 2 m, as required by the ICRW application. Further studies must show whether the accuracy is also sufficient for accident analysis. Together with the classic accident data (e.g. deformation of the vehicle), it may be possible to further increase the accuracy.

The information on heading, longitudinal acceleration, and yaw rate of the vehicles has a particularly high median accuracy across all test series, which, except for high decelerations, is always over 90% with low absolute median errors. The high accuracy of these parameters promises great potential for improvement in accident reconstruction. Because these data are not recorded in the EDR and are difficult to determine otherwise for reconstructing the accident scene, it would be a valuable source of accident data. Regarding the LCRW and ICRW applications, but also for other use cases, the measured accuracy should be sufficient.

The results of the accuracies of the individual parameters show that

the accuracy of some parameters could be estimated. For example, the position accuracy is dependent on the accuracy of the GPS and can also decrease with poorer GPS visibility. A significant finding, however, is that both speed and position accuracy are dependent on the longitudinal dynamics of the vehicle. This should always be considered when interpreting the values. The comparison of the measured accuracy and the confidence level of the heading of the vehicle itself during cornering also provides interesting results. While the measured accuracy also shows a small dependence on the yaw rate, this was not reflected by the confidence level within the CAM. Accordingly, it can be stated that changes in accuracy due to vehicle dynamics are not reflected by the confidence levels of the CAM, at least in the experiments shown in this work. This should be further investigated in future work.

With the examined parameters, the current status in space and time of the vehicle can be determined. But to calculate a collision risk or the accident scene of vehicles involved in an accident, a high accuracy of the common time base is also necessary. This was not explicitly investigated in this work, but a statement about this can also be derived from the high accuracies measured. Thus, both systems (ADMA and V2X module of the vehicle) used GPS time as a time base. A high inaccuracy between the two time bases would also have led to high inaccuracies of the investigation parameters. However, since this is not the case, it can be assumed that the time bases have a high agreement and thus accuracy.

Additionally, it should be noted that the measured accuracy was determined under best-case environmental conditions and full GPS reception. Position accuracy may decrease with poor GPS reception due to occlusion by buildings in cities or mountain valleys. A consideration of the environment and the GPS reception is given in the CAM by the respective confidence parameters. Unfortunately, only the heading confidence was supplied in the CAMs of the investigated vehicles. For a reliable determination of the current accuracy of the data, the sending of these values is crucial. In addition, the accuracy should be determined as a function of different confidence levels in future work.

Regarding the measured generation frequencies, it must be noted that these were also generated under best-case conditions. If the

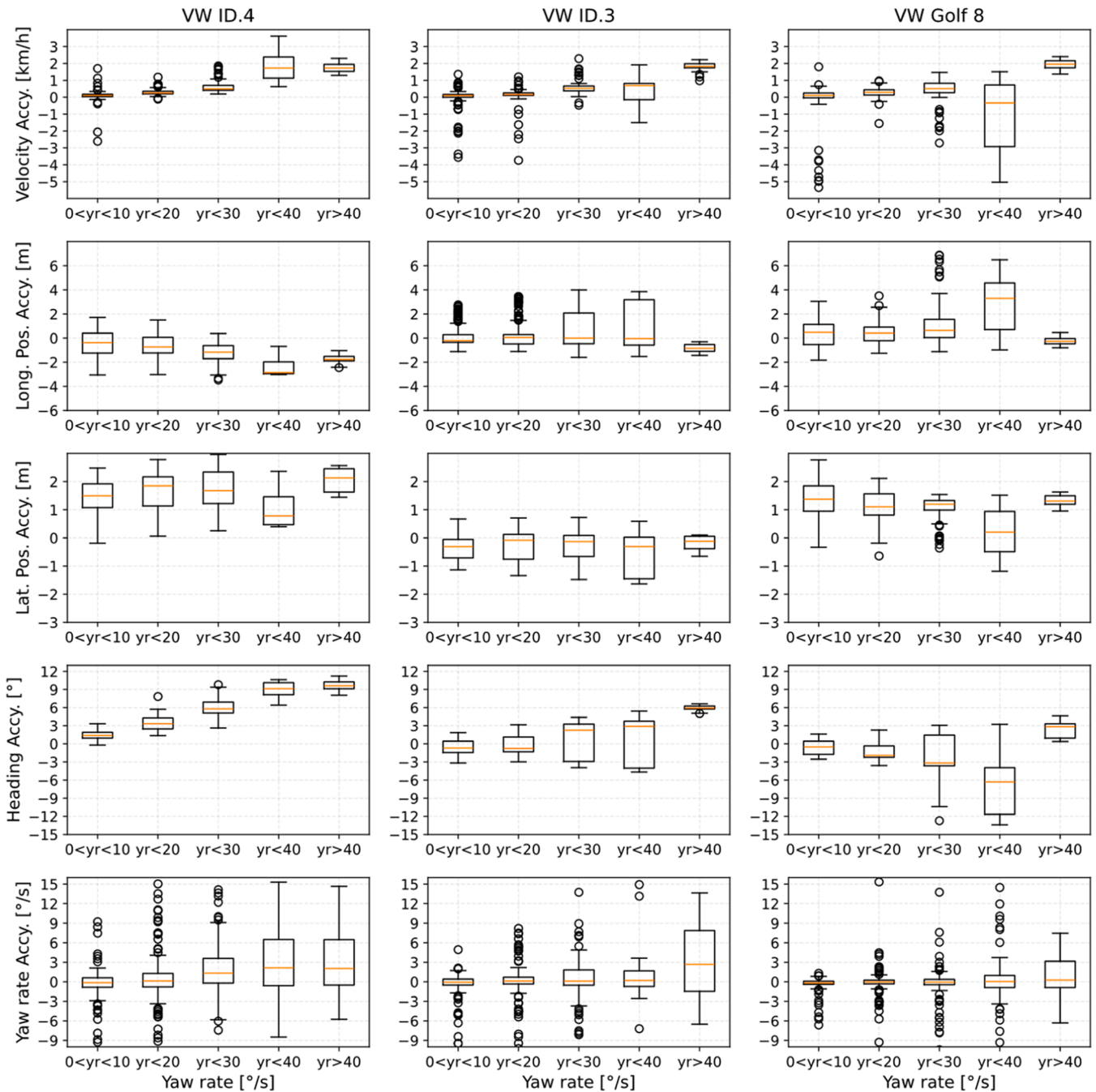


Fig. 16. Examination parameters are shown via yaw rate while cornering.

transmission channel is overloaded, this can lead to a reduction of the transmission frequency by using the Decentralized Congestion Control method [30,31]. Overloading of the transmission channel is possible due to a high density of connected vehicles or also due to an increase in the amount of data sent within the CAM if optional parameters are also sent.

Finally, it should be mentioned again that the values in the table describe the mean value of the statistical parameters of the three test vehicles. As already seen in the detailed evaluation, the accuracy improves towards ID.4. The ID.4 achieves a median longitudinal position accuracy of 82.3% and a lateral position accuracy of 80.1% in the tests for maximum acceleration. This shows the great potential of the CAM data as accident data in the future.

4. Conclusion

This study aimed to evaluate the accuracy of the parameters sent in Cooperative Awareness Messages (CAMs) by the first generation of commercial V2X-capable vehicles currently available on the EU market. The motivation of the investigation is that the CAM data have the potential to be used as digital accident data for accident analysis and other future use cases. For these use cases, and in general for the original vehicle safety use cases, a high degree of accuracy is necessary, and it is important to know the accuracy. This paper presents the outcome of driving tests at the CARISSMA test site, which systematically generated CAMs in well-defined scenarios based on the standardized message triggering rules and characterized the statistical properties of the available CAM data.

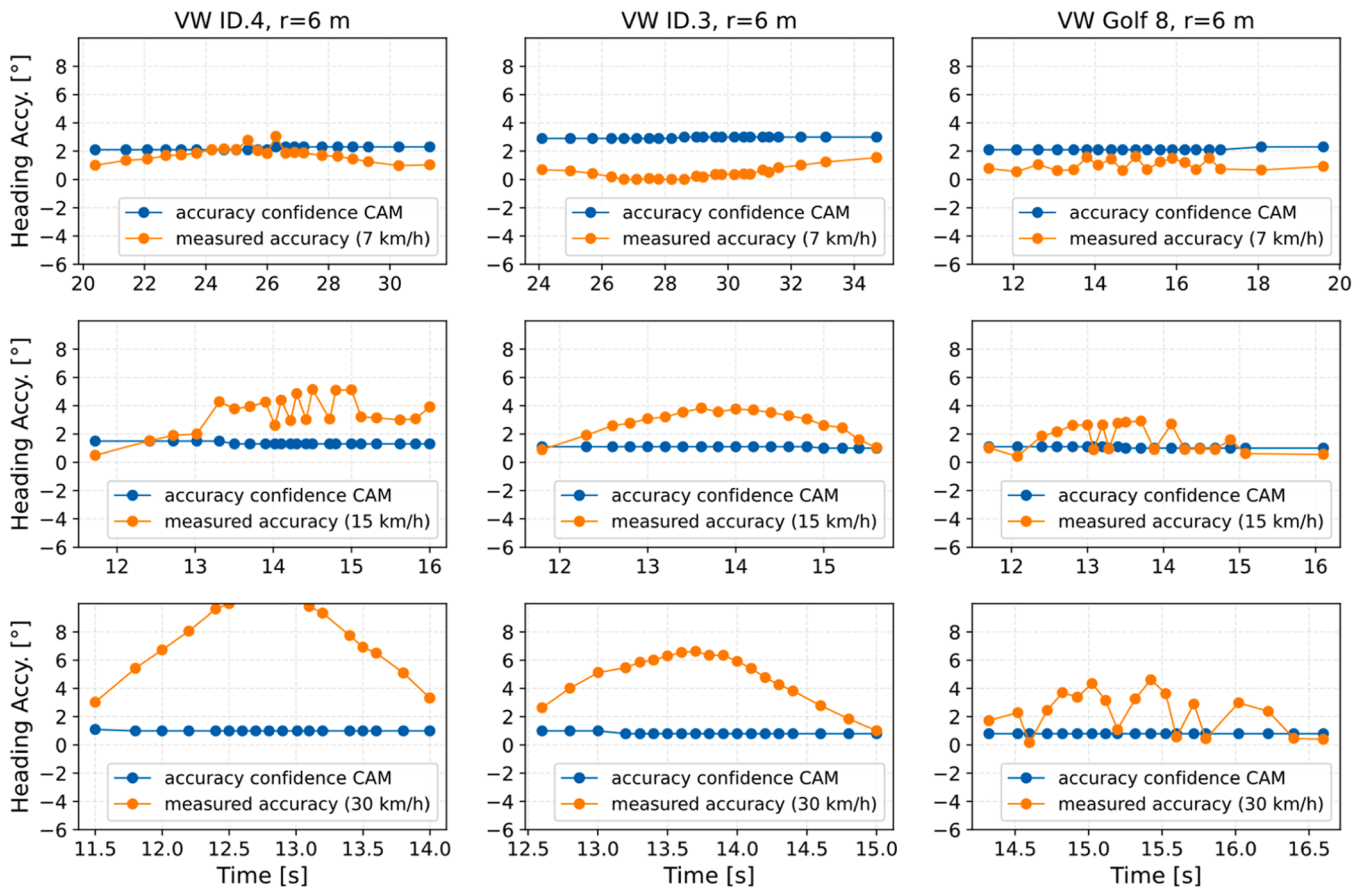


Fig. 17. Comparison of transmitted heading accuracy in the CAM with actual accuracy in tests for cornering with radius = 6 m.

Table 4

Statistical summary of the accuracy of all investigated parameters across all tests and vehicles as mean values of the determined medians, means, median absolute deviations and standard deviations per vehicle and test.

Mean Values	Standing	Accel. max	Decel. max	Const. v	Curve
dvelocity					
Median	/	2.98 km/h	8.88 km/h	0.33 km/h	0.27 km/h
Mean	/	3.05 km/h	8.37 km/h	0.31 km/h	0.35 km/h
MAD	/	1.47 km/h	3.63 km/h	0.20 km/h	0.57 km/h
SD	/	1.82 km/h	4.44 km/h	0.24 km/h	1.12 km/h
da_long					
Median	/	0.21 m/s ²	0.20 m/s ²	/	/
Mean	/	0.16 m/s ²	0.49 m/s ²	/	/
MAD	/	0.40 m/s ²	1.87 m/s ²	/	/
SD	/	0.76 m/s ²	2.90 m/s ²	/	/
dx					
Median	0.64 m	2.46 m	2.35 m	2.03 m	0.54 m
Mean	0.90 m	2.69 m	2.76 m	2.23 m	0.64 m
MAD	1.02 m	1.60 m	2.01 m	2.22 m	1.10 m
SD	1.35 m	1.96 m	2.54 m	2.66 m	2.57 m
dy					
Median	1.02 m	0.79 m	1.12 m	0.29 m	1.05 m
Mean	0.80 m	0.47 m	0.58 m	0.41 m	2.00 m
MAD	0.70 m	0.80 m	0.90 m	0.81 m	0.59 m
SD	0.87 m	0.95 m	1.03 m	1.03 m	2.00 m
dheading					
Median	0.26°	0.13°	0.04°	0.10°	1.94°
Mean	2.75°	0.23°	0.74°	0.11°	2.03°
MAD	8.09°	1.27°	1.97°	0.17°	2.42°
SD	22.14°	8.87°	10.67°	0.22°	3.96°
dyawrate					
Median	/	/	/	/	0.13 °/s
Mean	/	/	/	/	0.24 °/s
MAD	/	/	/	/	2.41 °/s
SD	/	/	/	/	4.40 °/s

Table 5

Relative accuracy of the test parameters summarized across all test vehicles and tests.

Mean Values	Standing	Accel. max	Decel. max	Const. v	Curve
velocity					
Median	/	90.0%	73.9%	99.7%	97.7%
Mean	/	82.4%	27.1%	99.7%	96.3%
a_long					
Median	/	90.7%	88.0%	/	/
Mean	/	70.8%	56.9%	/	/
x					
Median	84.0%	48.7%	44.4%	32.8%	82.8%
Mean	75.5%	47.9%	32.9%	32.0%	74.0%
y					
Median	42.9%	42.3%	37.2%	54.9%	43.2%
Mean	38.5%	40.7%	39.2%	49.7%	37.8%
heading					
Median	99.8%	99.9%	100%	100%	99.3%
Mean	98.8%	99.9%	99.6%	99.9%	99.1%
yawrate					
Median	/	/	/	/	94.0%
Mean	/	/	/	/	84.2%

As a result, the information on speed, heading, longitudinal acceleration and yaw rate has a high relative median accuracy of more than 88%. Except for high accelerations, the accuracy meets the requirements for the EDR (< 1 km/h). With high acceleration, the accuracy is still better than stated as a requirement in the literature for classical accident reconstruction. Only under heavy braking is this requirement no longer met. On the other hand, larger errors are observed for the position data. However, it should be noted that the data accuracy has already improved considerably with a newer vehicle model, the ID.4, presumably due to technical improvements compared to the older models ID.3

and Golf 8. Nevertheless, the median lateral position accuracy is better than the required 2 m of the ICRW application. The longitudinal position accuracy just meets the requirements of 2 m of the ICRW application when standing or cornering. Regarding the accident analysis the statistical description of the CAM parameters accuracy generated in Table 4 allows the CAM data to be used with an allowable tolerance range for accident reconstruction in court. The knowledge about the vehicle's position, acceleration, heading, and yawrate, especially in the accident scene, is a great advantage as this information is not stored in the EDR and is also difficult to determine by classical accident data. Together with the increase in position accuracy via the vehicle development age, this information could greatly improve the quality of accident analysis in the future.

Furthermore, findings on the dependence of the data on the kinematics of the vehicle could be determined. For example, the magnitude of the acceleration significantly influences the accuracy of the speed information of the CAM. In contrast, a speed dependency could be determined for the accuracy of the longitudinal position. On the other hand, most parameters are influenced by the yaw rate, which affects the accuracy of the speed and heading information and the scattering of the yaw rate itself.

In addition, the heading accuracy was compared with the accuracy sent by the vehicle. It should be noted that the vehicle estimates the yaw rate more conservatively than it does during maneuvers without yaw rate. At high yaw rates the actual accuracy of the heading decreases, which is not reflected by the transmitted heading accuracy by the CAM. Whether this also applies to the other parameters must be determined in further studies, as this can be critical for implementing applications and use cases.

Finally, the occurring generation frequencies have been evaluated. During the acceleration tests, we observed that the data were always sent at 5 or 10 Hz, with 10 Hz being the most frequently occurring generation frequency. At constant speed, the frequency depends solely on the speed and is usually sent reliably according to the trigger conditions. It should be noted that the trigger condition is not triggered by the indicated speed but by the vehicle's ground speed. The generation frequency concerning the yaw rate has the largest scattering at the end due to the difficulties in driving and reproducing the tests. However, a generation frequency of 10 Hz is difficult to achieve, and thus, the generation frequency during cornering is mostly 5 Hz or less. Compared to the EDR, accidents with accelerations above 1 m/s^2 , speeds above 30 km/h and curve speeds above 10 km/h in the accident scene would have higher generation frequencies than 2 Hz. The storage of the CAM would thus provide a better temporal resolution of the accident scene compared to the EDR.

In general, it can be stated regarding the accuracy of the data that

Appendix

these sometimes differed significantly among the test vehicles. Therefore, the accuracy presented in this paper are not necessarily applicable to the population of all vehicles, as the results were generated from only one manufacturer's vehicles. More tests will have to be conducted in the future, especially with vehicles from other manufacturers as soon as they are available in the market. However, we expect that the data accuracy will improve with the further development of V2X-capable vehicles. Thus, the CAM data can be of great benefit for accident analysis as a specific V2X use case.

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CRediT authorship contribution statement

Maximilian Bauder: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Andreas Festag:** Validation, Visualization, Writing – original draft, Writing – review & editing. **Tibor Kubjatko:** Supervision, Writing – review & editing. **Hans-Georg Schweiger:** Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

Data will be made available on request.

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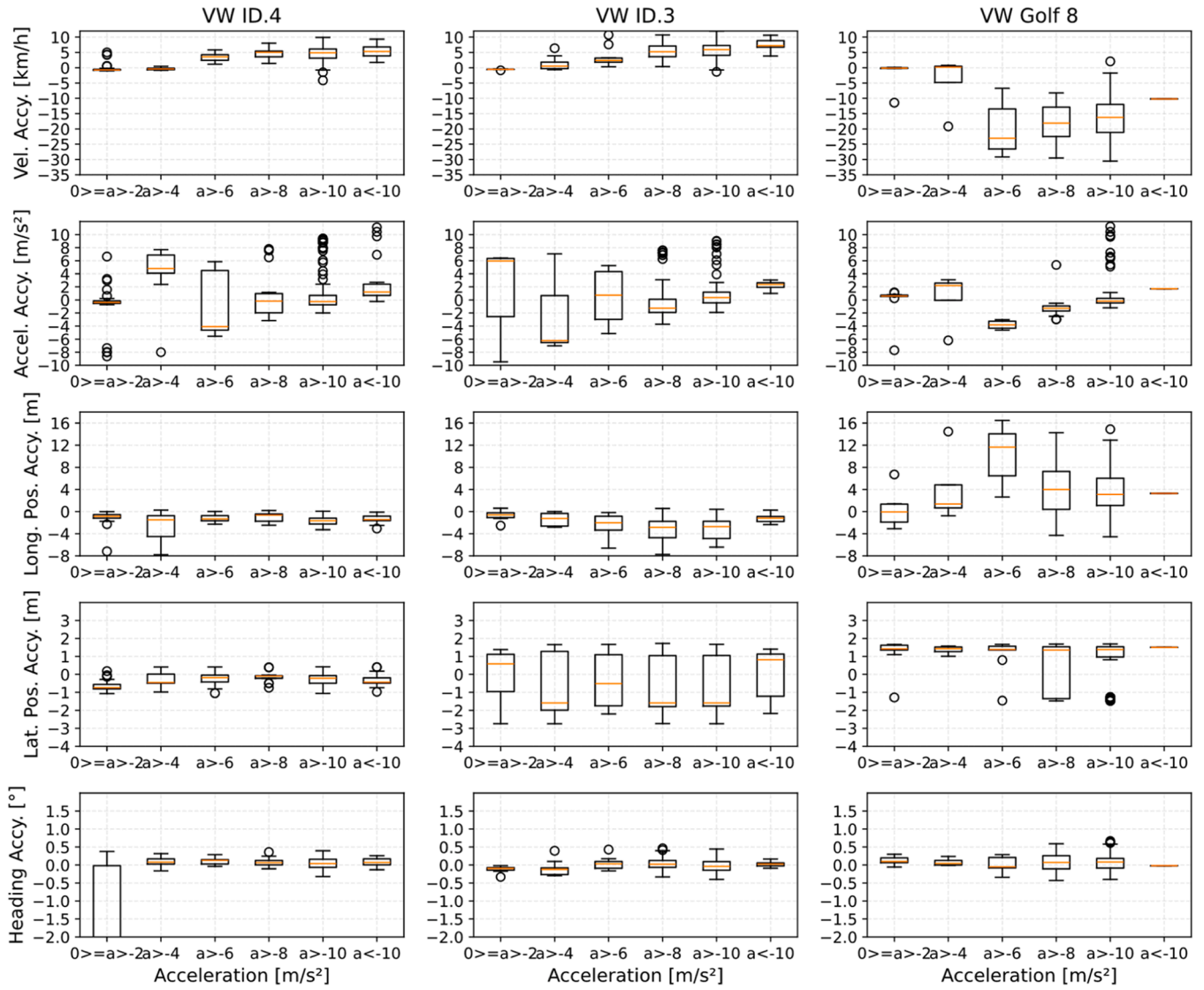


Fig. 18. Examination parameters are shown via acceleration at full deceleration.

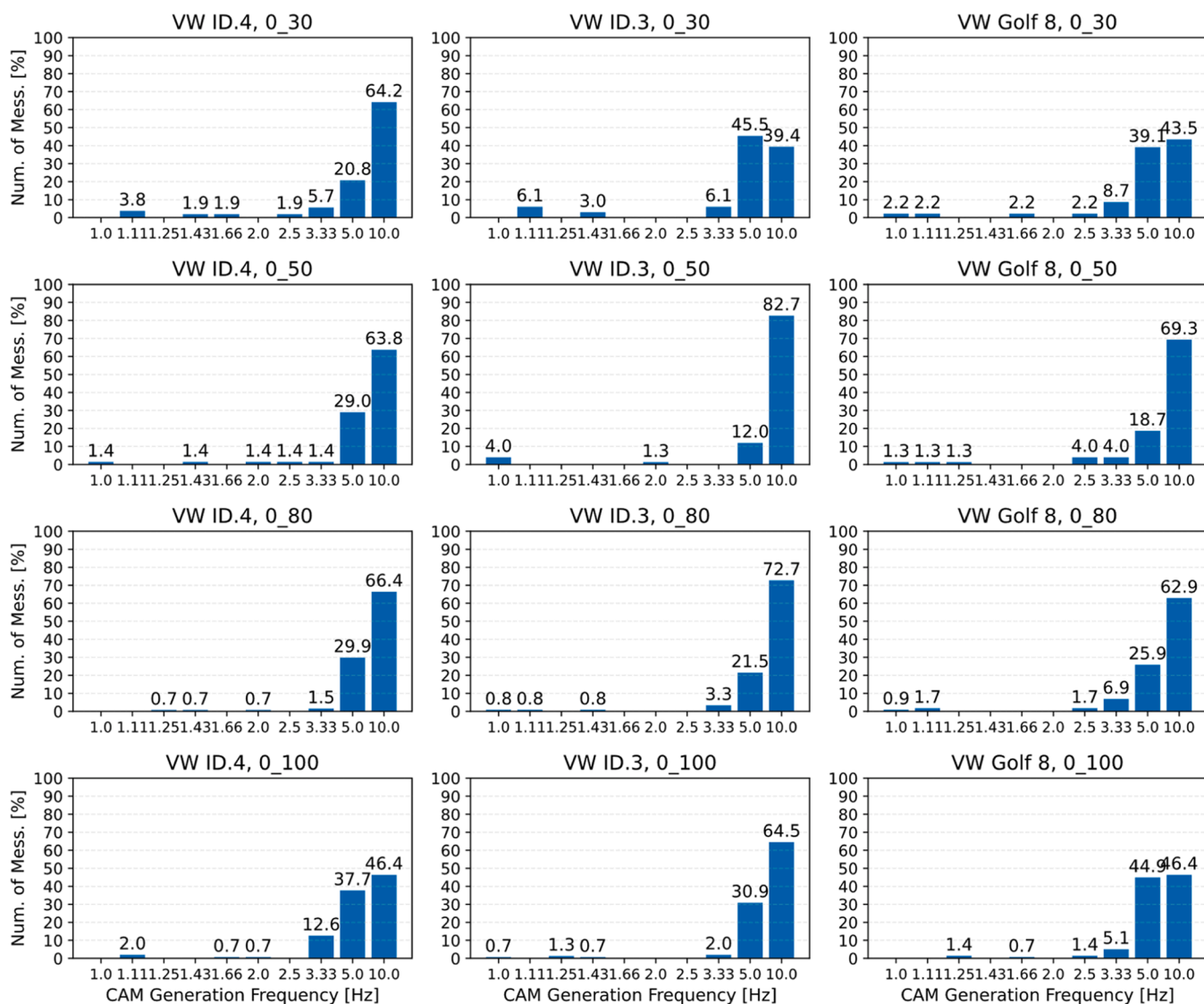


Fig. 19. Percentage distribution of the generation frequencies of the vehicles during full acceleration tests.

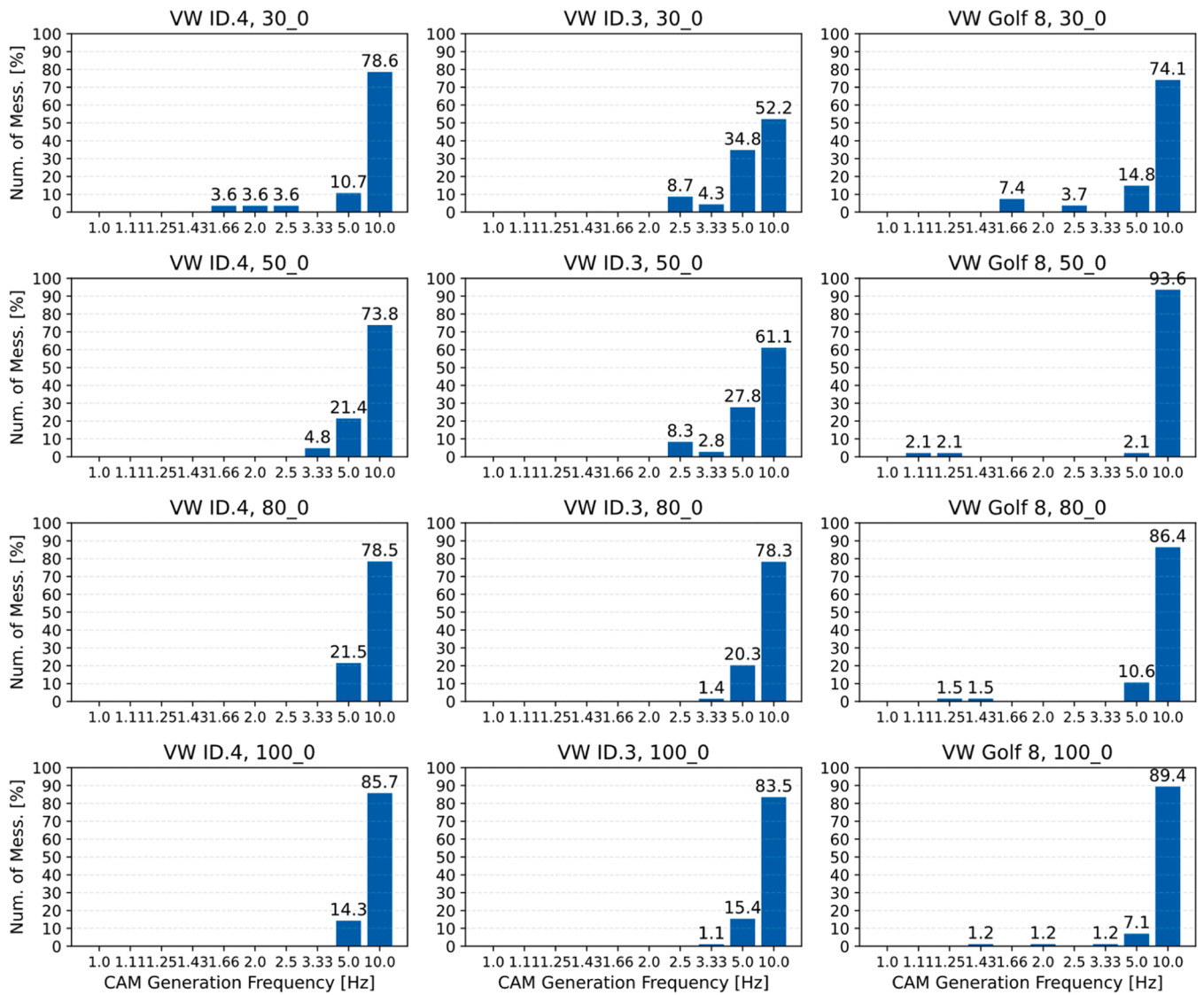


Fig. 20. Percentage distribution of the generation frequencies of the vehicles during full deceleration tests.

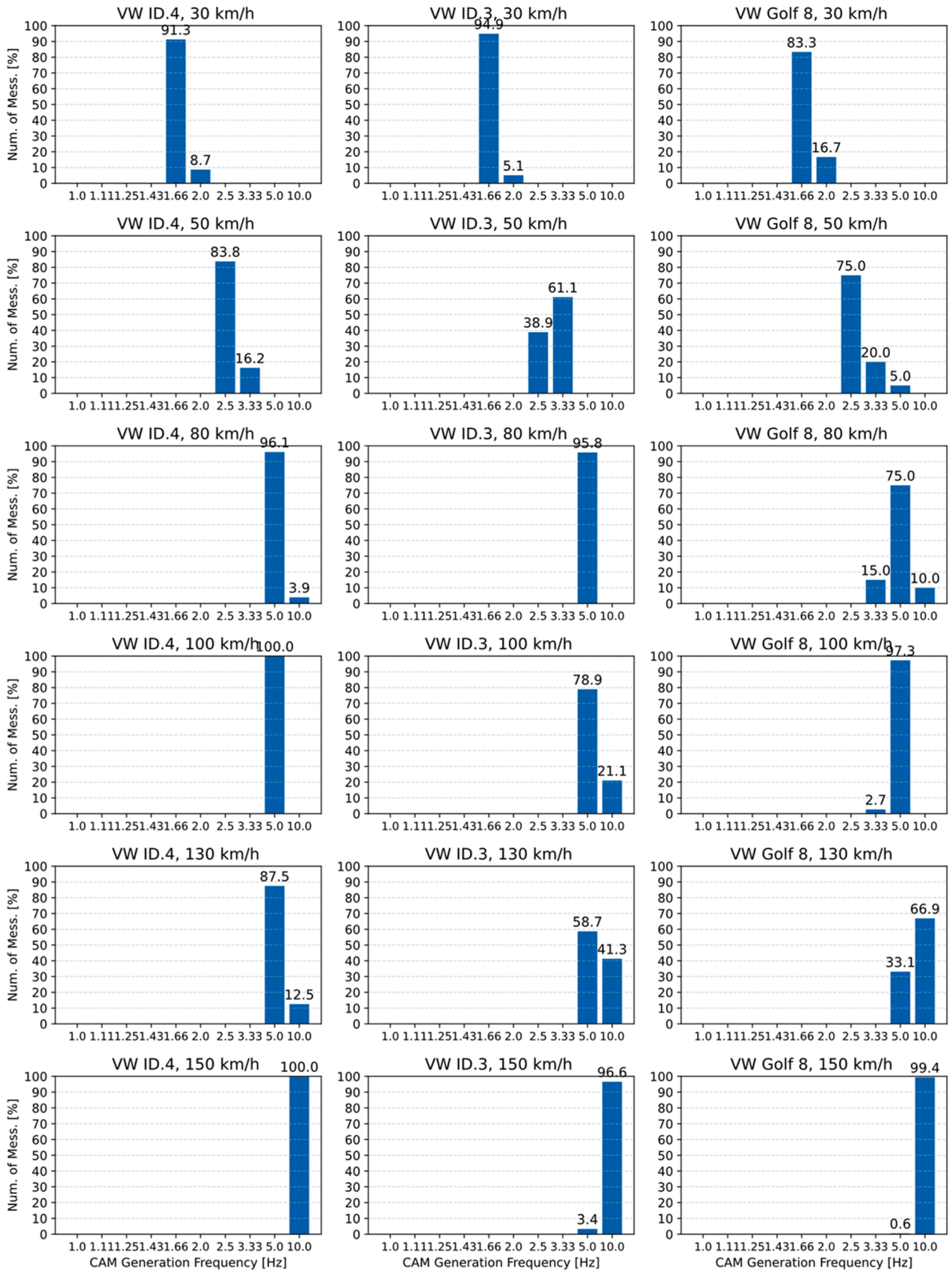


Fig. 21. Percentage distribution of the generation frequencies of the vehicles during constant driving tests.

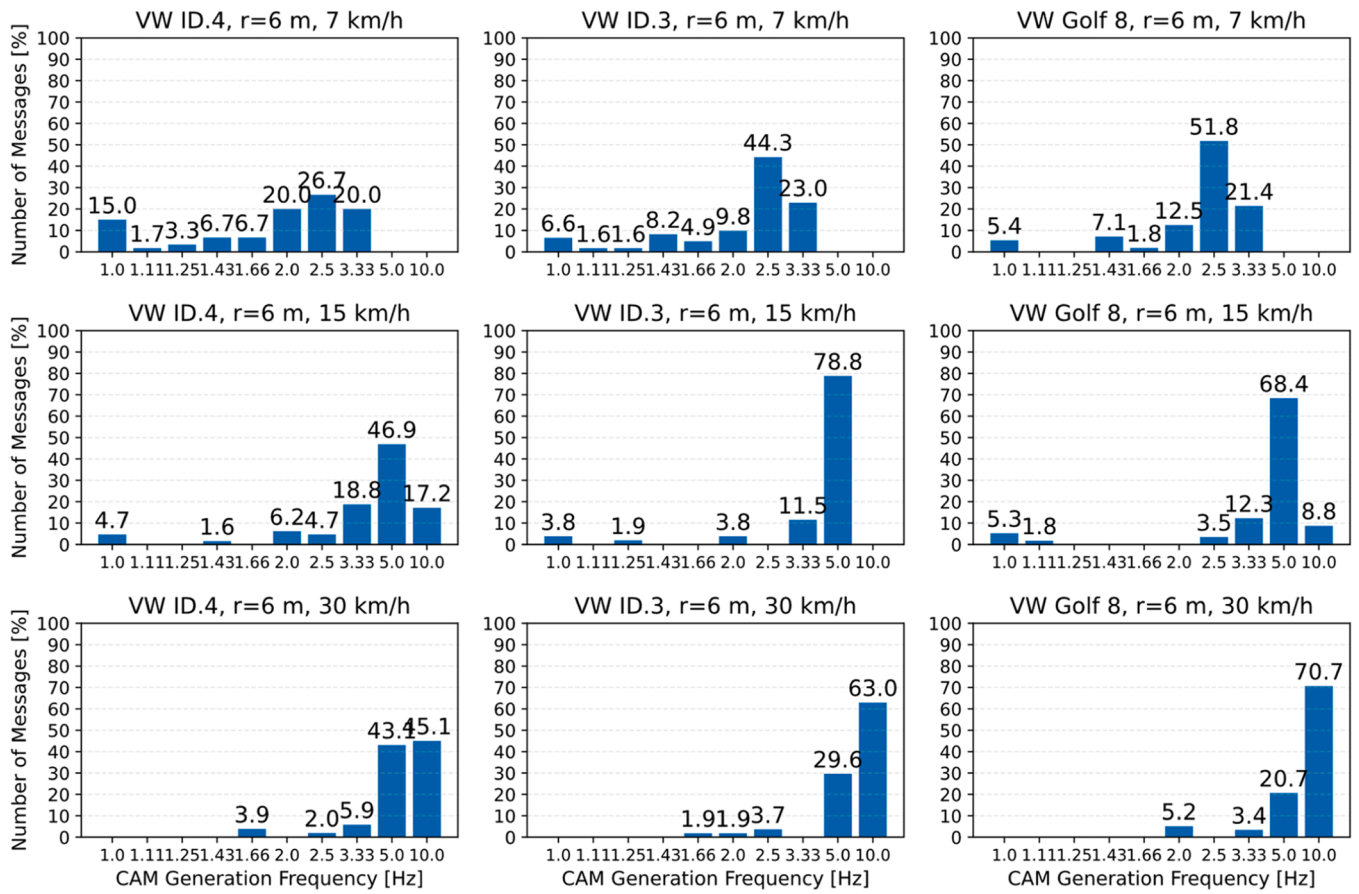


Fig. 22. Percentage distribution of the generation frequencies of the vehicles during cornering ($r = 6$ m).

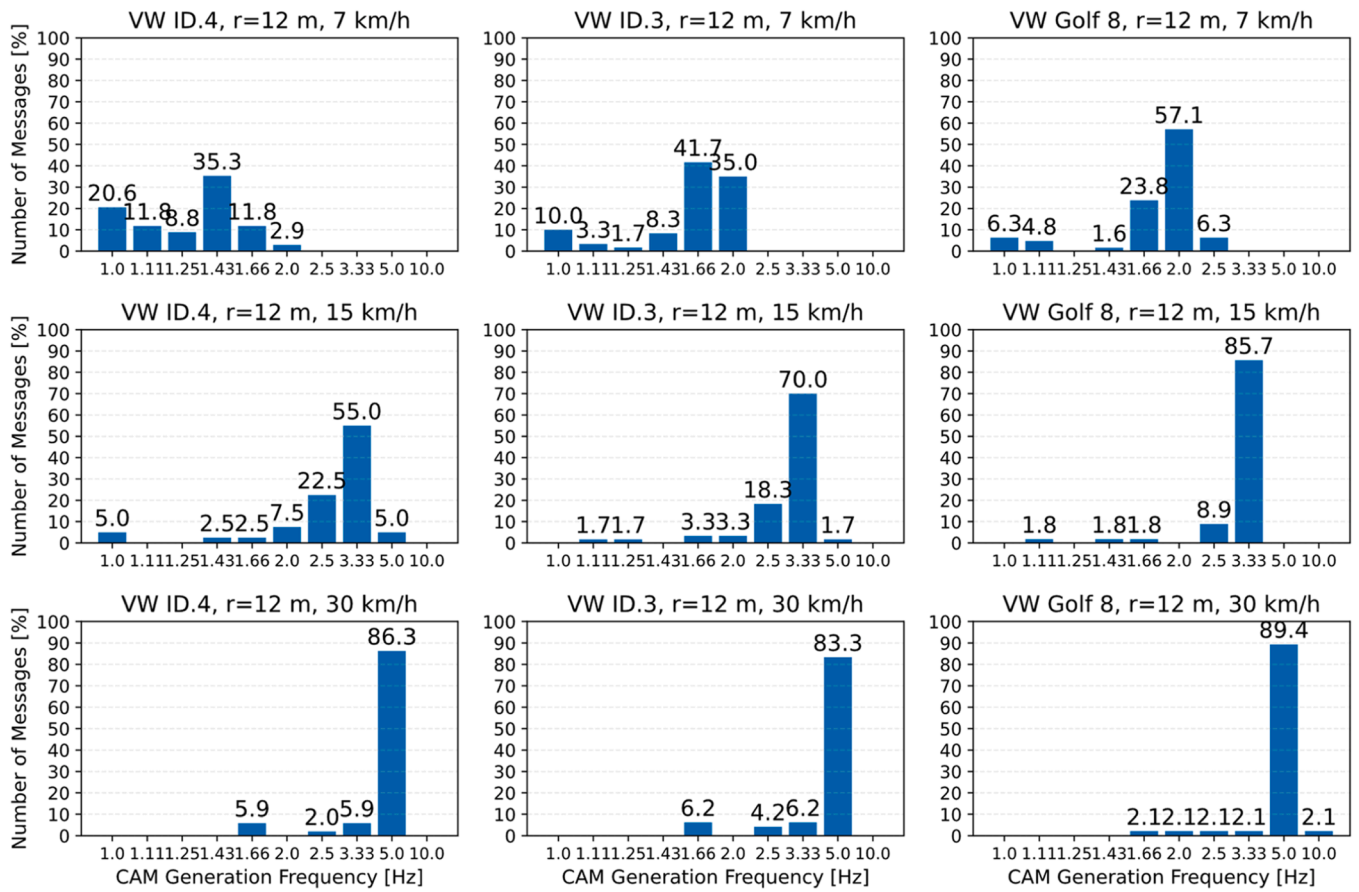


Fig. 23. Percentage distribution of the generation frequencies of the vehicles during cornering ($r = 12$ m).

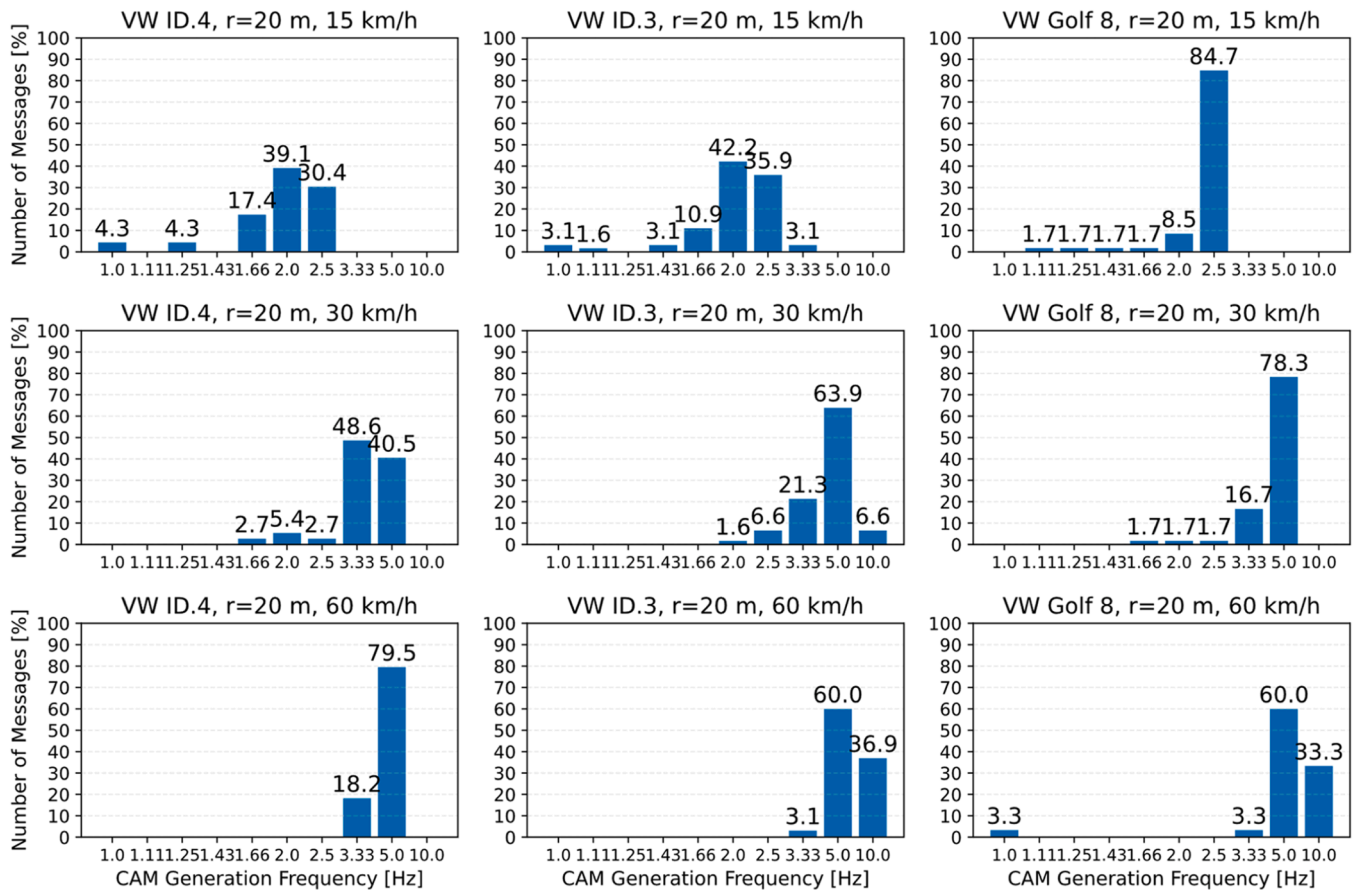


Fig. 24. Percentage distribution of the generation frequencies of the vehicles during cornering ($r = 20$ m).

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