Compact accident research No. 114

# Perception of electric vehicles



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Unfallforschung der Versicherer
Wilhelmstraße 43/43 G, D-10117 Berlin
Postfach 08 02 64, D-10002 Berlin
Phone +49 (0)30 20 20 – 58 21, Fax +49 (0)30 20 20 – 66 33
www.udv.de, www.gdv.de, unfallforschung@gdv.de

**Content**
Sophie Kröling, M.Sc.

**Realisation**
pensiero KG, www.pensiero.eu

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## Introduction

In road traffic, pedestrians must use visual and acoustic information to assess the movement of vehicles in order to avoid collisions with a vehicle for example when crossing a road. Pedestrians are among the most vulnerable road users. In 2020, a total of 26,130 pedestrians were involved in crashes with personal injury [1]. Most of the road users killed in urban areas were walking [1].

The most common mistakes in urban traffic accidents happen when pedestrians cross the street [1]. Such accidents can occur due to misjudgment of approaching vehicles. The time until a vehicle reaches the pedestrian's position (TTC: time-to-collision) is overestimated and dangerous crossing decisions are made. The precise estimation of vehicles is already difficult at constant vehicle speeds [2]. In urban traffic, however, it frequently occurs that vehicles accelerate in order to reach a green light phase, for example. Due to the increased rotational speed of an internal combustion engine, pedestrians can usually detect this characteristic auditory information. Electric vehicles, on the other hand, can accelerate very powerfully, but without emitting the sounds that are familiar from internal combustion engines.

Since July 2021, all newly registered hybrid and electric vehicles must be equipped with an AVAS (Acoustic Vehicle Alerting System) (European regulation) [3]. The system must generate warning sounds at low speeds that ensure an acoustic detectability of electric vehicles at a similar level as for vehicles with internal combustion engines. According to the regulation, this system may be switched off at a speed of 20 kilometers per hour, since it is assumed that at higher speeds the tires and no longer the engine causes the main part of the driving noise. The regulation states that the AVAS should achieve a minimum sound pressure level and indicate vehicle behavior, such as acceleration or reversing [3]. In addition, with each gear, the frequency range must change in proportion to the speed [3]. In this context, it is not precisely prescribed how exactly the AVAS should sound. However, so far there are no findings on how well pedestrians can take into account the acceleration of electric vehicles (with and without AVAS) compared to internal combustion engine vehicles when making crossing decisions.

## Aim of the project

The aim of the present research project was to investigate how well the acceleration of electric vehicles (with and without AVAS) is perceived compared to vehicles with internal combustion engines. From this, conclusions should be drawn as to whether new hazards, especially for pedestrians, can be expected with the increasing number of electric vehicles. The detailed research report no. 76 "Risk of high acceleration? Road crossing behavior of pedestrians in interaction with electric vehicles (with and without AVAS) compared to vehicles with internal combustion engine" (in German) is available on the UDV website at www.udv.de [4].

On behalf of the German Insurers Accident Research (UDV), the Johannes Gutenberg University Mainz conducted **three experiments** on the combined visual and auditory perception of vehicles in an urban street crossing scenario. In each case, the focus was on the comparison between electric vehicles (with and without AVAS) and vehicles with internal combustion engines, especially in situations in which the approaching vehicle accelerates toward the pedestrians.

**In the first experiment**, the perception of the TTC of electric vehicles was examined in comparison to vehicles with internal combustion engines. The participants were asked to estimate when the vehicle would reach their own location.

**In the second experiment**, the behavior of pedestrians was investigated using crossing decisions. The participants were asked to decide whether or not they would cross the street in front of an approaching vehicle.

**In the third experiment**, it was examined whether the acceleration of vehicles is detected or not. The participants were asked to assess whether an approaching vehicle was accelerating or traveling at a constant speed.

These three experiments were combined in the present study to analyze the role of driving sounds from different perspectives relevant to a road crossing by pedestrians.

## Audiovisual virtual reality simulation system

In order to experimentally assess the role of vehicle sounds in the perception of acceleration as realistically as possible, an audiovisual virtual reality simulation system was created, that is unique to date (Fig. 1).

For this purpose, audio recordings of various vehicles were recorded on a test track:

- **A** of a vehicle with internal combustion engine (Kia Rio 1.0 T-GDI 120),
- **B** of an electric vehicle without AVAS (Kia e-Niro, AVAS deactivated) and
- **C** of the same electric vehicle with AVAS (Kia e-Niro, AVAS activated).

The sound of the AVAS installed in the vehicle met the requirements of the European regulation [3]. In contrast, however, it could be deactivated. If activated, it was active up to a speed of 28 kilometers per hour.

Several microphones on the vehicles and on the track recorded the driving sounds. The vehicle positions were recorded using high-precision GPS. To record vehicle sounds at different driving profiles, the vehicles each drove at different constant speeds as well as low and high acceleration. Table 1 provides an overview of the intended driving profiles. After in-depth quality control and exclusion of, for example, recordings with loud background noise, 93 suitable recordings were selected.

Due to the driving characteristics (e.g., manual vehicle control, gear changes, etc.), the intended driving speed profiles could not be implemented exactly in every case. Therefore, the analysis did not directly compare the actual speeds (e.g., by comparison tests). Instead, regression models were used. These models statistically predict the parameters for perception, behavior, and detection for the intended driving profiles. In these models, the actual speeds and the vehicle types (three variants) are included as separate factors. Thus, the influence of the vehicle type could be separated from a possible influence of the driving characteristics and thus the influence could be controlled. Analyses using comparison tests show comparable results (cf. [4]).

In a laboratory, 16 loudspeakers in a circular array were installed (Fig. 1). Using this array, the participants heard a realistic spatial acoustic simulation of the approaching vehicles and a background noise of a quiet residential area. In addition, the participants were shown a visual environment via head-mounted display which depicted an inner-city, two-strip road with no other



***Figure 1*** · Left: Setup of the 16 speakers in the laboratory and visual presentation of the street scene with vehicle. Right: Participant with head-mounted display.

## Intended driving profiles

*Table 1 · at constant speeds, low acceleration and high acceleration*

| | Constant speed drives | | | | | Low acceleration | | | | High acceleration | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Acceleration in m/s²** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.6 | 0.6 | 0.6 | 0.6 | 2.0 | 2.0 | 2.0 | 2.0 |
| **Speed in km/h** | 10 | 20 | 30 | 40 | 50 | 10 | 20 | 30 | 40 | 10 | 20 | 30 | 40 |

traffic or road users (Fig. 1). A vehicle with a driver was presented on the street. The participants' head movements were captured by the laser-based tracking of the head-mounted display, allowing them to look around the virtual scene.

All participants had good eyesight and hearing, which was tested in advance.

## TTC estimation

In the first experiment, the participants were asked to estimate the TTC of the vehicles. This is defined as the time at which the vehicle would arrive at the participants' position. Accurate estimation of the TTC is particularly important for preparing a road crossing.

### Methodology

In the simulation, the participants stood at the side of a two-lane road (see Fig. 1). The standing vehicle could be seen in the lane on the left. With one press of a button by the participant, the vehicle drove off, accelerated eventually after two seconds, and faded out after a total of five seconds of visibility and audibility. The participants were then asked to press a button on the controller when they thought the vehicle would have reached their position if it had continued to move toward them at the same constant speed or acceleration as in the visible and audible phase. This experimental method is well established in research on TTC estimation and has been tested widely (e.g. [2]). The different driving profiles were presented as shown in Table 1 and described in Chapter 2. TTC was defined as the time from when the vehicle faded out until it reached the position of the participant. For each vehicle type and each of the driving profiles, contact times of 2.0 seconds, 3.5 seconds and 5.0 seconds were presented. Thus, the vehicle would have taken different lengths of time to arrive at the participant's position at the time of fade. Each of these 93 combinations were randomly presented to the participants in each of seven runs. The experiment lasted a total of about five hours per participant, with corresponding preparation and break times.

A total of 30 people participated in the first experiment. 25 of them were women, five men. They were between 18 and 63 years old (M = 26.37 years, SD = 8.87 years).

## Selected results

In summary, it was found that the TTC of the electric vehicles (with and without AVAS) under acceleration were estimated to be significantly longer and tended to be overestimated than for vehicles with internal combustion engines. This means that the time until the vehicle arrived at the own location was estimated to be longer than it actually was. Such an estimate could lead to riskier road crossings in front of approaching electric vehicles, compared to internal combustion engine vehicles.

Figure 2 shows the estimated TTC as predicted by the regression model created on the basis of the actual speeds and accelerations, taking the initial speed of ten kilometers per hour as an example. The x-axis shows the acceleration in meters per second squared, and the y-axis shows the TTC estimated by the participants. The actual TTC at which the vehicle would have actually reached the participants' position is shown in the graph by the purple dashed lines (left 2 s, center 3.5 s, right 5 s). Accordingly, the three graphs show the results for different temporal distances between the vehicles and the participant's location at the time of fading. For an actual TTC of five seconds, the vehicles were farther away in time than for lower TTCs. It is apparent that the TTC estimates for the internal combustion engine vehicle (ICEV, red line) are close to the actual contact time (purple dashed line). The electric vehicle without AVAS (EV, red line), on the other hand, was estimated to continue at a constant speed rather than accelerate from the time of fading. The acceleration is not considered adequately. As the acceleration increased, and as the actual TTC increased, the TTC was increasingly overestimated. The acceleration of the electric vehicle with AVAS (EV AVAS, green line) was slightly better considered in the TTC estimation, but not as well as for the vehicle with internal combustion engine. The difference between the overestimated TTC for the electric vehicles and the more accurately estimated TTC for the internal combustion engine vehicle became larger with increasing acceleration and longer actual TTC.

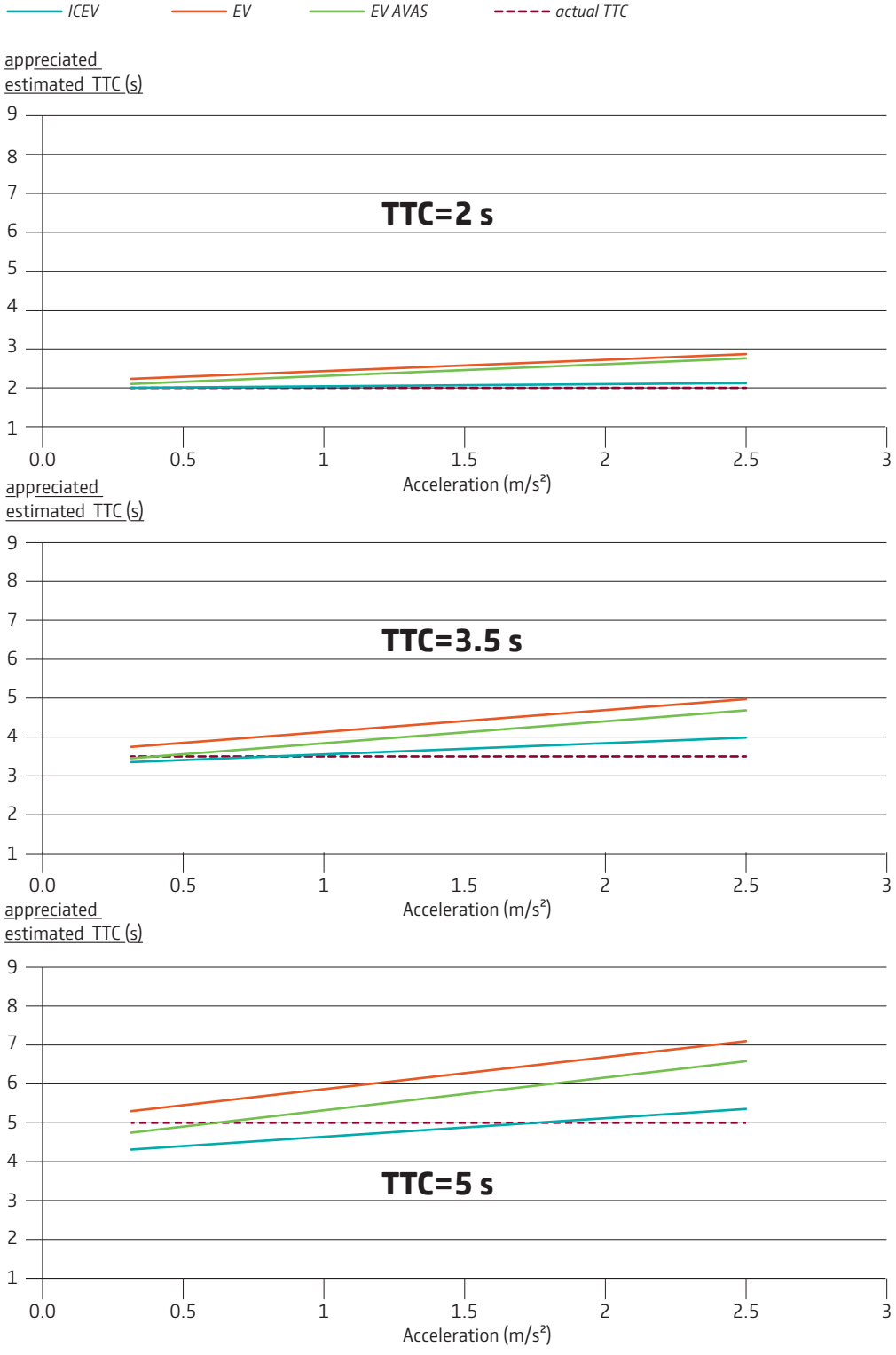
At an initial speed of 20 kilometers per hour, a similar picture emerged (without illustration).

The results show that acoustic information (driving sounds) is used to estimate TTCs when the vehicle is accelerating. The electric vehicle (with and without AVAS) apparently does not provide information on acceleration as well as the vehicle with an internal combustion engine. The AVAS slightly improves the TTC estimates, but it does not reach the level of the vehicle with internal combustion engine.

At **constant speeds**, the TTCs of the different vehicles were estimated similarly. There were no significant differences between the TTC estimates for the electric vehicle (with or without AVAS) and the internal combustion engine vehicle. This means that at constant speed, the acoustic differences between the electric vehicle and the internal combustion engine vehicle do not play a significant role in the TTC estimates.

## Predicted TTC estimates for acceleration

***Figure 2*** **· Initial speed: 10 km/h, actual TTC: 2 s, 3.5 s and 5 s**




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# Street crossing decisions

The results of the first experiment show that the TTC for accelerating electric vehicles is overestimated. On average, the participants assumed that the vehicle would take longer to reach their position at the time of estimation than it would in fact. This could lead to riskier crossing decisions. Which crossing decisions are actually made by participants in situations with accelerating electric vehicles and vehicles with internal combustion engines was therefore investigated in the second experiment.

## Methodology

In the second experiment, the participants were again standing on a simulated street in an inner-city environment. Directly opposite the participant was a door on the other side of the street. A straight line between the position of the participant and the door indicated the crossing path. The approaching vehicle started moving at the push of a button and faded out after a presentation time of five seconds. The participant was then asked to decide by pressing a button whether or not he or she would have crossed the road in front of the vehicle at the time of fade-out. In the experiment, different TTCs were presented at the time of fading. Based on the relation between the TTC at the time of fading and a positive crossing decision, the collision probability was determined. Assuming that the vehicle would not brake in response to the pedestrian (worst-case scenario), a collision between vehicle and pedestrian would occur if the TTC at fading is shorter than the time required to cross the road. To calculate the collision probability from the response data, the average crossing time of each participant was determined in advance on a route that corresponded to the length of the road crossing in the simulation. Based on the individual crossing duration and the relation measured in the experiment between the TTC at the time of fading and a positive crossing decision, it was possible to calculate how likely a collision would have been.

The vehicle with internal combustion engine as well as the electric vehicles (with or without AVAS) approached, as in the first experiment, with a selection of constant speeds or accelerations (see driving profiles in Tab. 1). A total of between 1,261 and 1,701 runs were presented randomly. The experiment lasted a total of about five and a half hours per participant.

A total of 25 people participated in the second experiment. 18 of them were women, seven men (age M = 22.84 years, SD = 3.87 years).

## Selected results

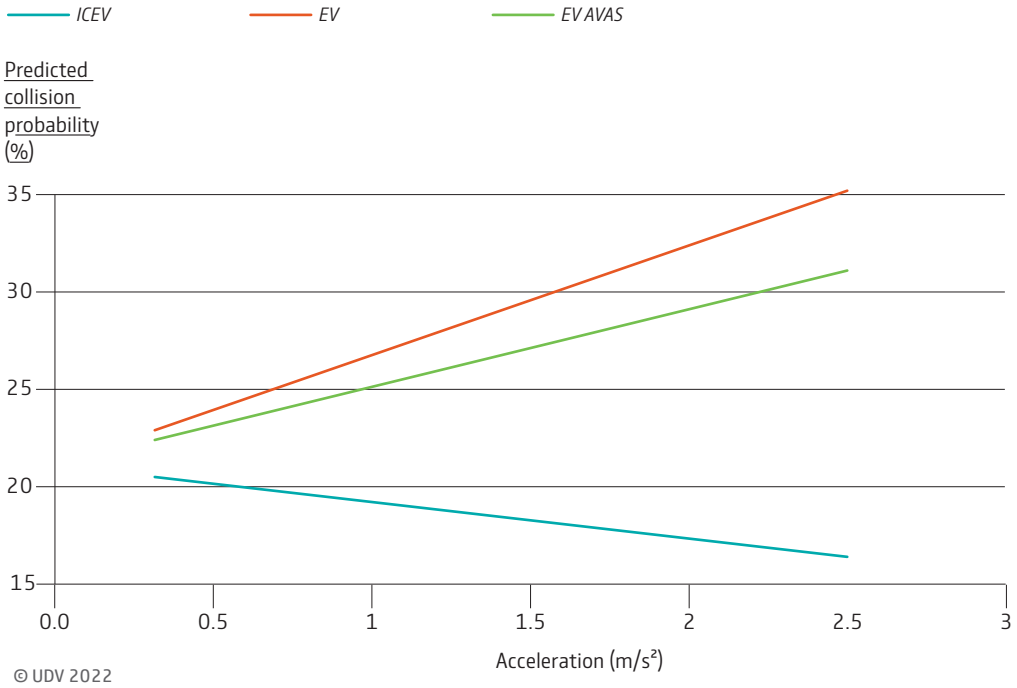
In summary, under **acceleration**, higher collision probabilities were shown for the electric vehicles (with and without AVAS) than for the vehicle with an internal combustion engine.

In Figure 3, the x-axis again shows the acceleration in meters per second squared. The y-axis shows the mean collision probability in percent, as predicted by the regression model fitted to the actual speeds and accelerations. For the internal combustion engine vehicle (ICEV, blue line), the collision probability was lower than for the electric vehicles and did not increase as the acceleration increased. The collision probabilities were lower for the electric vehicle with AVAS (EV AVAS, green line) than for the electric vehicle without AVAS (EV, red line), but still significantly higher than for the vehicle with internal combustion engine (ICEV, blue line). In contrast to the vehicle with an internal combustion engine, the collision probability for the electric vehicles (with and without AVAS) increased significantly with increasing acceleration. The overall collision probabilities observed in the experiment are higher than they probably would be in real traffic. The participants may have made riskier crossing decisions in the objectively harmless laboratory situation than they would in real traffic. Therefore, only the relations between the vehicle types are used to interpret the effects, not the absolute values. It can be assumed that at high accelerations riskier crossing decisions are made in interaction with electric vehicles (with and without AVAS) than in interaction with vehicles with internal combustion engines.

For all **constant speeds**, the collision probability was below 20 percent. Neither the vehicle types nor the velocities showed a significant effect on the collision probability.

## Collision probability for the acceleration drives

***Figure 3*** · **Predicted average collision probability p**




# Acceleration detection

A possible explanation for the effects from the first and second experiment would be that the acceleration of the electric vehicles is not detected because the corresponding characteristic engine sounds, as they occur in a vehicle with an internal combustion engine, are missing. To investigate this, the detection of acceleration was examined in the third experiment.

### Methodology

In the third experiment, two vehicles were presented to the participants in each trial at intervals of one second for three seconds each. One vehicle accelerated and the other drove at a constant speed. After the presentation, the participants were asked to decide by pressing a button which of the two had accelerated. In the analysis, the proportion of correct answers was examined. A value of 1.0 corresponds to an acceleration detection performance of 100 percent. The participant would have correctly detected the accelerating vehicle in all trials. A value of 0.5 corresponds to a guessing probability of 50 percent, since there were only two possible answers in each case.

The electric vehicles (with and without AVAS) and the internal combustion engine vehicle were presented in a selection of driving profiles shown in Table 1, which included both acceleration and constant speeds. In addition, the vehicles were presented either visually only, that is, with visual presentation but without driving sounds, or audiovisual, that is, with visual presentation and driving sounds.

A total of 896 trials were presented to each participant randomly. The experiment lasted about five hours per participant.

In the third experiment, 14 people participated, nine of them women and five men. Their mean age was 24.43 years (SD = 4.29 years).

## Selected results

The results are shown in figures 4 and 5. The y-axis shows the hit rate of the acceleration detection. Thus, higher values mean better acceleration detection. The lower horizontal line (p = 0.5) represents the guess probability. On the x-axis the acceleration is plotted (in $m/s^2$, low or high). The blue lines represent the results for visual presentation only, the red lines for audiovisual presentation. The left graph shows the results for the vehicle with internal combustion engine (ICEV), the middle graph shows the results for the electric vehicle without AVAS (EV), and the right graph shows the results for the electric vehicle with AVAS (EV with AVAS).

At the **lower acceleration** (0.6 $m/s^2$; 10 km/h initial speed) in the visual-only presentation, the detection performances of all vehicles were close to or even equal to the guess probability (Fig. 4; blue, left in each graph). Thus, when presented visually only (without vehicle sounds), the low accelerations were hardly detectable. This is consistent with previous studies (e.g., [5]). The audiovisual presentation (red) significantly improved acceleration detection. This effect was strongest for the vehicle with internal combustion engine (ICEV, left), followed by the electric vehicle with AVAS (EV with AVAS, right). When the vehicle sounds were additionally presented, the acceleration of the vehicle with internal combustion engine was detected in about 90 percent of the cases, the acceleration of the electric vehicle with AVAS in about 85 percent. In contrast, the acceleration of the electric vehicle without AVAS (EV, center) was detected in only about 65 percent of the cases. The acceleration of the electric vehicle without AVAS was thus detected significantly worse than that of the vehicle with internal combustion engine and the electric vehicle with AVAS. The AVAS therefore has a positive effect, particularly at low accelerations, as the acceleration is detected more frequently.

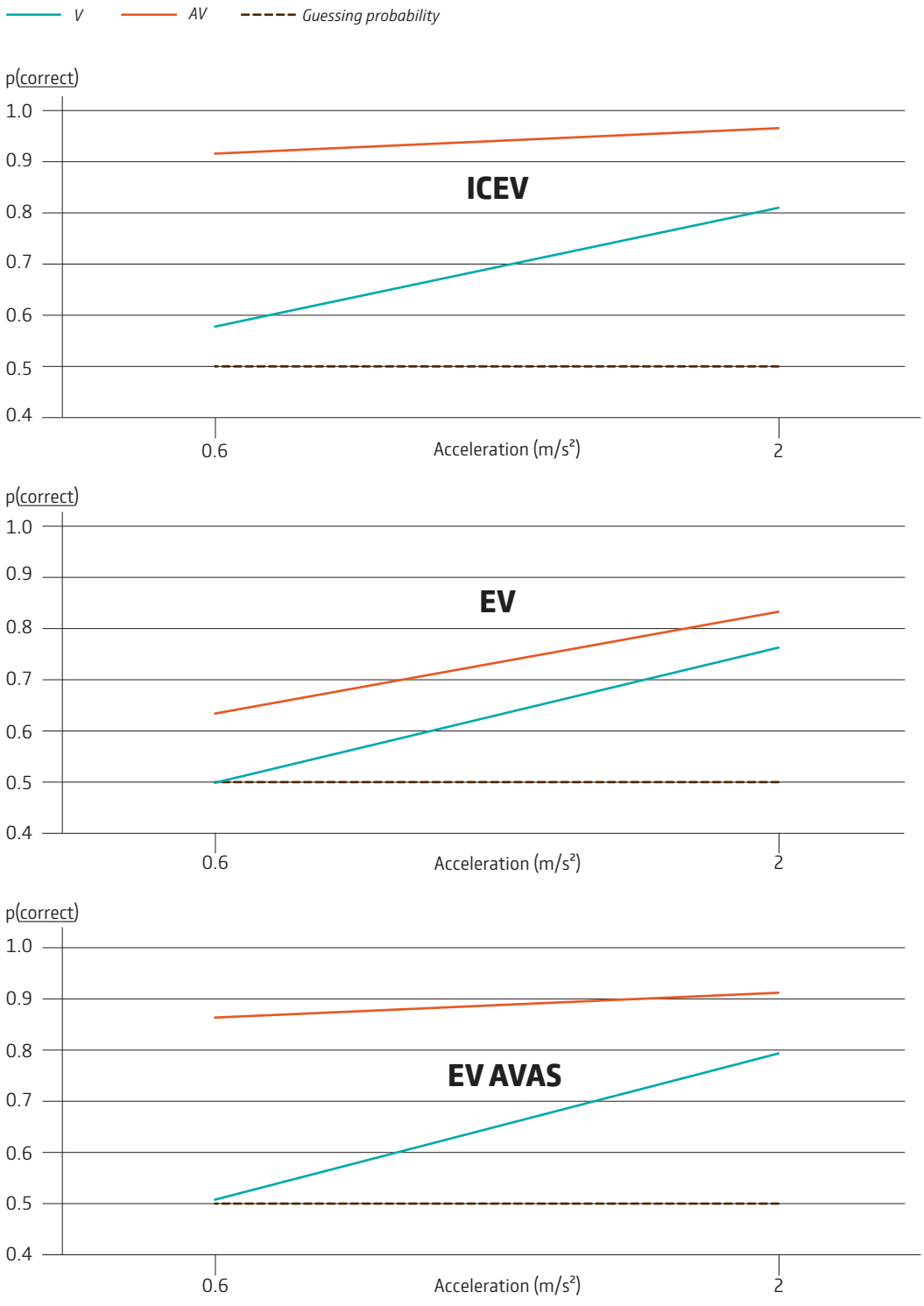
At the **higher acceleration** (2 $m/s^2$; 10 km/h initial speed), the acceleration was also recognized quite well in the visual only presentation. In figure 4, this can be seen from the fact that the response quality for the visual presentation (blue dots on the right side of the graphs) was significantly higher than the guessing probability and higher than for the low acceleration (0.6 $m/s^2$). When vehicle sounds were added, the detection performance improved (red). Again, the participants detected the acceleration of the vehicle with internal combustion engine best (ICEV, left), followed by the electric vehicle with AVAS (EV with AVAS, right). The acceleration of the electric vehicle without AVAS (EV, center) was detected least well. However, the difference between acceleration detection performance for the electric vehicles with or without AVAS was not statistically significant for the higher acceleration.

A similar picture emerged for the **higher acceleration** at an initial speed of 30 kilometers per hour (Fig. 5). This only includes the comparison between the electric vehicle without AVAS and the vehicle with an internal combustion engine, as the AVAS in the test vehicle was only active at speeds up to 28 kilometers per hour. With audiovisual presentation (red), acceleration was detected more frequently by the test subjects than with visual presentation only (blue). This effect was stronger for the vehicle with internal combustion engine (ICEV, left) than for the electric vehicle (EV, right).

In summary, participants recognized acceleration significantly better with audiovisual presentation, when driving sounds were presented in addition to visual information, than with visual presentation only. However, there were differences in the extent of improvement between the vehicles. While the acceleration of the vehicle with internal combustion engine was detected much better from the vehicle sounds, the detection rate for the electric vehicle without AVAS improved notably less. At low acceleration, these differences were more severe. Thus, without AVAS, the acceleration of an electric vehicle is worse to detect. With AVAS, acceleration is significantly better to detect than without, at least at low acceleration. It is not as well detected as in a vehicle with an internal combustion engine, but better than in an electric vehicle without AVAS.

## Acceleration detection

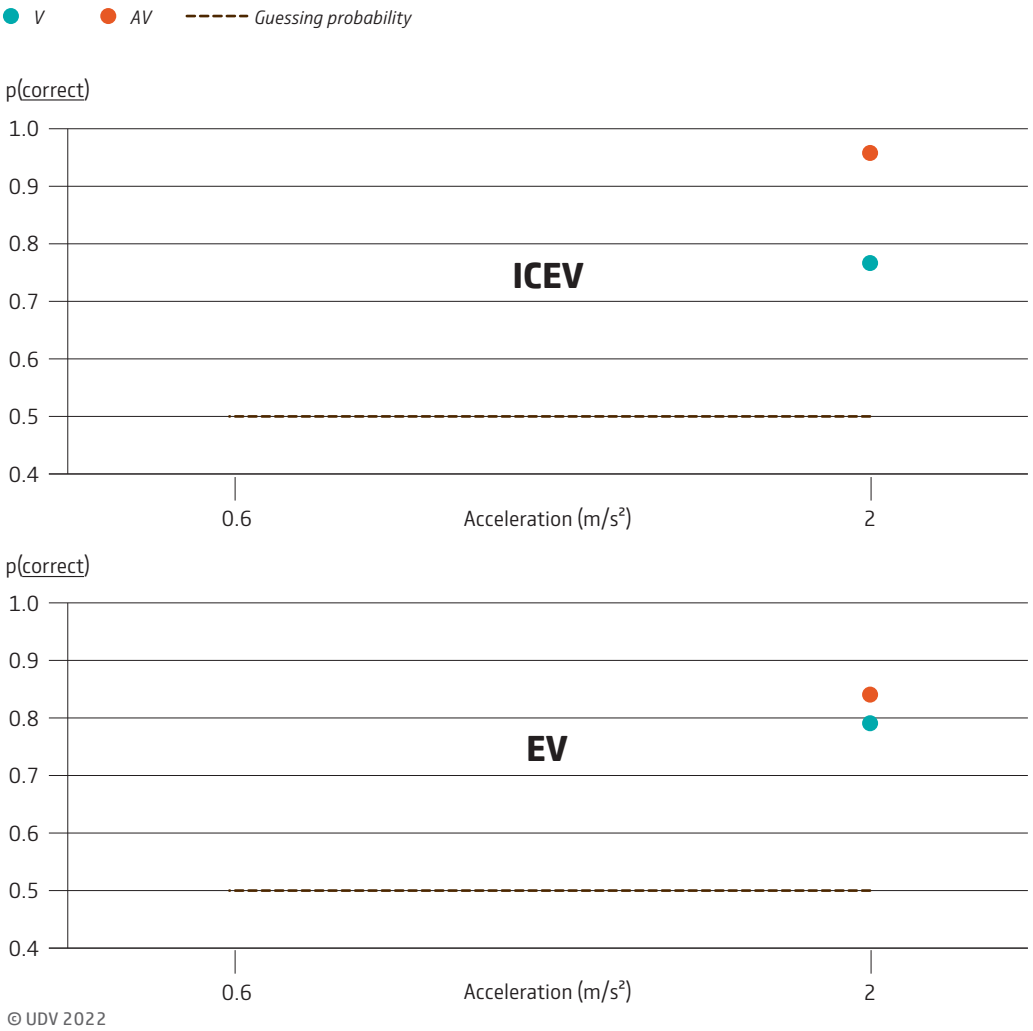
***Figure 4*** · **Probability of acceleration detection p (correct responses) at low and high acceleration; Initial speed: 10 km/h, V: visual presentation only, AV: audiovisual presentation**




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## High acceleration detection

***Figure 5*** · **Probability of acceleration detection p (correct responses) at high acceleration; Initial speed: 30 km/h, V: visual presentation only, AV: audiovisual presentation**




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# Summary and discussion

In the present study, an audiovisual virtual reality simulation system was used, in which the driving sounds of different vehicles in a street crossing situation were presented realistically. By means of this system, the audiovisual perception of electric vehicles with and without AVAS in comparison to vehicles with internal combustion engines could be investigated for the first time, from the perspective of pedestrians.

When driving at **constant speed**, there were hardly any differences between electric vehicles with and without AVAS and the vehicle with an internal combustion engine. The TTC estimates were close to the actual TTCs. There were also hardly any differences between the vehicle types in the crossing behavior of pedestrians. Thus, the differences in driving sounds did not play a significant role.

Under **acceleration**, however, the TTCs of the electric vehicles were significantly overestimated, whereas the TTC estimates for the vehicle with internal combustion engine were more accurate (first experiment). Overestimation of TTCs could lead to risky situations in traffic because the vehicles are estimated by pedestrians to arrive later than they actually do. The results suggest a systematic underestimation of acceleration in TTC estimation, which is referred to as first-order estimation. Acceleration is not adequately taken into account for electric vehicles. Instead, TTCs are estimated as if the vehicles continue to travel at a constant speed. Although AVAS improved the estimates, it did not reach the level of the internal combustion engine vehicle. This was also reflected in the crossing behavior of the pedestrians (second experiment). Riskier crossing decisions were made in front of accelerating electric vehicles (with and without AVAS) than in front of the accelerating vehicle with an internal combustion engine, even at higher speeds. The probability of collision was up to 10 percent higher at high acceleration than for the internal combustion engine vehicle. Although the AVAS mitigated this effect, the collision probability was still significantly higher than for the internal combustion engine vehicle. Thus, even in situations where pedestrians can see the vehicles well, they additionally use acoustic information to estimate the acceleration of vehicles. For accelerating electric vehicles (with and without AVAS), this acoustic information is apparently insufficient. Pedestrians are less able to interpret it and consequently make riskier crossing decisions.

More inaccurate TTC estimates and riskier crossing decisions could be at least partly due to the failure to detect the accelerations of electric vehicles, especially without AVAS (third experiment). However, the accelerations of internal combustion engine vehicles and electric vehicles with AVAS were detected similarly well. Because TTC estimation was less accurate and crossing decisions were riskier for electric vehicles with AVAS than for the internal combustion engine vehicle, it can be assumed that accurate estimation does not depend solely on acceleration detection. Thus, the AVAS contributes to the detection of acceleration. However, additional information obviously contributes to the concrete vehicle's movement estimation, which is more useful for vehicles with internal combustion engines than for electric vehicles.

It must be noted that only one vehicle model and thus only one specific AVAS was considered in this study. However, the range of AVAS variants is wide due to the design scope described in the beginning. Whether and how different implementations of the European regulation may also affect perception in crossing situations must be analyzed in the future.

The participants in the present study had good eyesight and hearing. However, people with impairments are also present in road traffic. Especially for persons with impaired vision, the acoustic information of vehicles could be even more relevant and the differences between the vehicle types possibly even greater.

# Conclusion

Pedestrians use both visual and acoustic information to estimate the movement of vehicles. Accelerating electric vehicles, however, appear to give pedestrians inadequate acoustic information, resulting in risky situations in traffic. The results of the study show that an AVAS that complies with the European regulation improves the perception of accelerating electric vehicles in a road crossing situation but does not achieve the accuracy of perception of an internal combustion engine vehicle. There appears to be room for improvement in the design of AVAS with respect to the acoustic signature under acceleration. Furthermore, the aspect of road crossing should be considered in addition to providing a basic acoustic detection of vehicles in the development of AVAS technologies. Legally, AVAS are only required to be active up to 20 kilometers per hour. However, as the present study shows for the first time, there are deficits in the assessment of electric vehicles compared to vehicles with internal combustion engines even at higher speeds. An extension of the speed range of the AVAS should therefore be discussed.

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GDV
DIE DEUTSCHEN VERSICHERER

Wilhelmstraße 43 / 43G
10117 Berlin
Phone: + 49 (0) 30 20 20 – 58 21
Fax: + 49 (0) 30 20 20 – 66 33

unfallforschung@gdv.de
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