Regular Article

Monika Ucińska* and Małgorzata Pelka

The effectiveness of the AEB system in the context of the safety of vulnerable road users

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Abstract: According to the analysis by the National Police Headquarters, roughly 40% of all road accident victims in Poland are vulnerable road users (VRU), i.e. pedestrians and cyclists. Their protection has become one of the priorities for action regarding road safety. For this purpose, various activities are carried out aimed not only at human behaviour or the development of modern and safe road infrastructures but also at the development of modern vehicles, including advanced driver assistance systems (ADAS). In order to identify the limitations of the currently available driver assistance systems, designed to respond to VRU, research was carried out under the project name, “PEDICRASH: Safety aspects of VRU in CAD automated vehicles.” The project was aimed at increasing users’ awareness (both pedestrians and drivers) of the limitations of ADAS by analysing barriers and indicating recommendations allowing for more effective protection of pedestrians and cyclists due to the identified operating limitations of these systems. The research focused on the autonomous emergency braking (AEB) system and its potential impact on the level of road safety, with particular emphasis on VRU.

Keywords: advanced driver assistance systems, autonomous emergency braking, road safety, vulnerable road users

1 Introduction

Road accidents are one of the most significant social problems of modern times. Their negative social, psychological,

and economic consequences affect millions of people. This has resulted in undertaking various actions to reduce the number of road accidents. 22,660 people lost their lives on EU roads in 2019 [1]. Despite a significant improvement in the level of road safety in Europe from 2010–2019, the results of the analysis show how far the actual statistics for accidents and their victims differ from the assumptions of European strategic plans such as “Vision Zero” [2].

The only countries that came close to a 50% reduction in the number of road fatalities from 2010–2019 were Norway (–48%), Greece (–45%), and Switzerland (–43%) (Figure 1). As a result, the objective to reduce road traffic fatalities by 50% was extended till 2030 [3].

Vulnerable road users (VRU) account for the largest share of road accident victims across Europe. This group includes pedestrians, cyclists, moped drivers, and motorcyclists. According to the European Transport Safety Council report [4], at least 51,300 pedestrians and 19,450 cyclists lost their lives on EU roads between 2010 and 2018. In 2018 alone, 5,180 pedestrians and 2,160 cyclists were killed in road accidents in the EU. This is about 30% of all road traffic victims.

Most of the accidents (approx. 70%) involving VRU occur in built-up areas. Between 2015 and 2017, 57% of all cyclist deaths occurred on urban roads in the EU. This is despite relatively lower average speeds in urban areas. According to the statistics, another 25% of pedestrian deaths in the EU occur on rural roads. Collisions with pedestrians far from urban centres may be subject to less frequent reporting of this type of accident.

It should be noted that, compared to other countries, Poland stands out as having an exceptionally high risk for pedestrians. Despite some positive changes in reducing the number of pedestrian deaths (averaging 6% each year in Poland), pedestrian mortality in Latvia, Lithuania, and Poland is still among the highest in the European countries. Statistical data show that these values are, respectively, 27, 25, and 22 people per million inhabitants (Figure 2).

In 2019, 7,005 accidents involving pedestrians (23.1% of the total road accidents) were recorded in Poland, in which 793 pedestrians (27.3% of the total fatalities) died,

* **Corresponding author: Monika Ucińska**, Motor Transport Institute, Transport Telematics Centre, Jagiellońska 80, 03-301 Warszawa, Poland, e-mail: monika.ucinska@its.waw.pl

Małgorzata Pelka: Motor Transport Institute, Transport Telematics Centre, Jagiellońska 80, 03-301 Warszawa, Poland, e-mail: malgorzata.pelka@its.waw.pl

Figure 1: Reduction of road fatalities in 2010–2019. Source: “authors” elaboration based on ref. [3].

Figure 2: Pedestrian deaths reported by the police (2016–2018 average) per million inhabitants. Source: ref. [4].

and 6,361 were injured (17.9% of the total injured people). The incidents involving them are mainly classified as “hitting a pedestrian.” The greatest number of accidents and casualties among pedestrians were caused by drivers

of passenger cars. The main cause (11% of all accidents) was that pedestrians did not give way at road crossings. As a result, 199 people died (8.9% of all fatalities) and 2,888 (9.1% of all injured people) were injured [5].

It should be noted that when a collision occurs, even at low speed, the chance of surviving for the VRU is very small. Most pedestrian accidents result in serious injury or death.

Although autonomous emergency braking (AEB) system is designed to detect vehicles, pedestrians, and cyclists, it has greater limitations for the VRU group. The pedestrian and cyclist recognition system operates at a lower speed range than the system used for the recognition of larger objects such as vehicles.

It should also be emphasized that the recognition of VRU is much more difficult than a vehicle, even in a straight section in good weather conditions.

The reaction time is one of the basic factors influencing traffic situations, including accidents, and forms part of the time it takes the car to stop. It is defined as the time during which the system or object (another participant of the traffic) responds to the transmitted signal (the time that passes from the activation of the stimulus to the moment of motion initiation). In general, the reaction time can be divided into three phases (the values of the reaction times of individual phases result from experimental studies – these times are given for 85–95% of the population) [6]. The first phase is the perception time (which ranges from 0 to 0.7 s), which is related to the perception of the stimulus and depends on the position of the object (another participant of the traffic, obstacle) in the driver's field of view (FOV) as well as on the contrast between the object and the background, and on the object's movement in relation to the surroundings. The second phase is the time to recognize the object, obstacle, and make a decision (which ranges from 0.2 to 0.6 s). This depends, among other things, on the necessity to perform various activities (and with an increase in the number of activities, e.g. use of a vehicle horn, braking, and turning, this time increases). If a previously made decision is corrected, this time may be longer than 0.6 s. The third phase is the physical reaction time/motor time – this is the interval between the initiation of movement (muscle stimulation, change of tension, initiation of a physical reaction to a stimulus, etc.) and its end [7]. It largely depends on the type of manoeuvre to be performed. Therefore, it is different for braking (from 0.25 to 0.7 s), which involves transferring the leg from the accelerator pedal to the brake pedal, than for turning, which requires a reduction in speed and then acceleration (0.2 s). Also, the time required for the operation of the respective vehicle system should also be taken into account.

If the driver expects danger, then the reaction time is assumed to be 0.5–0.8 s. If the driver is attentive but does not expect danger, then the reaction time is assumed to

be 0.7–0.9 s. When the driver drives the vehicle carelessly, then the reaction time is assumed to be 1.4–1.9 s [8]. Based on the results of experimental studies on driver reaction times in various road conditions and situations, it is assumed that the average driver's reaction time to a sudden appearance of an obstacle or object on the road is from 0.7 to 1.0 s. Only people with special mental predispositions, well-rested, and concentrating are able to shorten this time to about 0.3 s, while maintaining a constant reaction time.

2 AEB system

The prevailing hope for an increase in road safety lies in the systems for automating driving and assisting the driver, referred to as advanced driver assistance systems (ADAS) [9,10]. Depending on the degree of automation, these systems can warn the driver about the danger or take control of the vehicle [11]. Thus, they can shorten the driver's reaction time, accelerating the moment of danger detection. Four classes of functions that were previously implemented by the driver are subject to automation. These are:

- Obtaining information
- Information processing
- Making a decision
- Performing control activities

One of the most common systems that is able to improve the level of road safety is the AEB system. Automatic/AEB systems to prevent rear-end collisions are already in production and have been since 2003 [12].

The aim of the study designed at the Motor Transport Institute, conducted at the test track, was an evaluation of the effectiveness and identification of the limitations of, *inter alia*, the AEB system in the context of VRU.

The main task of the AEB system is to monitor the space in front of the vehicle and detect obstacles in the vehicle's path. The system is designed to prevent or reduce the severity of frontal collisions with parked vehicles and vehicles, pedestrians, and cyclists moving in the same lane and same direction, oncoming pedestrians, and cyclists from the side. The AEB system in most vehicles is based on the joint operation of cameras at the top of the windscreen and radar installed at the front of the vehicle.

Figure 3 describes the zone monitored by the AEB system.

The space in front of the car is monitored at all times and the probability of a collision is calculated. The speed

Figure 3: AEB obstacle detection zone. Source: author's own study based on ref. [13].

and position of the vehicle are analysed, and sometimes also the trajectory of its movement.

When an obstacle is detected, the system sends information about the danger to the driver and then the system pushes the brake pads onto the brake discs and increases the pressure in the brake system to increase braking power. If the driver does not react, the system will attempt emergency braking. In some vehicles, when the driver attempts to avoid an obstacle, the system will assist in the manoeuvre by monitoring and correcting steering wheel movement to maintain the most favourable course. System operation can be interrupted by pressing the accelerator pedal or firmly moving the steering wheel.

The system operates in the speed range from 5 to 250 km/h. In most vehicles, at speeds in the range of 10–30 km/h, the vehicle has the ability to stop in front of

an obstacle (it is possible to use safely in limited areas such as zone 30, shared spaces, living areas, etc.). At higher speeds, the system's task is to reduce the effects of a collision by reducing speed. However, it should be remembered that the system was developed for low speeds and many vehicles will not even initiate braking at speeds greater than 100 km/h. The system may not work when taking a sharp curve or when electronic stability control intervenes.

The general principle of the system's operation is presented in Figure 4.

In 2015 [14], a study conducted by Euro NCAP and NCAP confirmed the high effectiveness of AEB systems, which could lead to a 38% reduction in real-world rear crashes at low speeds [15]. According to estimates by the European Commission, in the EU alone, AEB systems could save more than 1,000 lives every year [16].

Figure 4: The principle of operation of the emergency braking system. Source: "authors" own study based on ref. [13].

There are many publications on the evaluation of the effectiveness of the AEB system as well as the limitations associated with it. Saadé [17] reviewed the literature on the impact of AEB systems on pedestrians and cyclists in terms of reducing the number of accidents and the severity of injuries. The results of various studies seem to be consistent and show that AEB is effective in reducing the number and severity of accidents involving pedestrians and cyclists. The effectiveness of the systems can range from 2.2 to 84% depending on the parameters for system performance measurement that have been taken into account.

The effectiveness of the AEB system, i.e. the potential benefits (avoidance of collisions and mitigation of injuries) and the limitations of the system in the context of a vehicle-cyclist mutual reaction, set in the situation of a potential frontal collision, was tested by Chajmowicz et al. [18]. The analyses of accidents related to AEB and cyclists were made on the basis of police data, based on which the risk curves of fatal, serious, and minor injuries to cyclists were first built. The effect of AEB on these cases was then simulated using a kinematic model of a car, including device operation strategies. By combining the obtained simulated impact velocity distributions with the injury risk curves, the effectiveness of AEB was evaluated in terms of the number of lives saved and the reduction in the number of injuries. An analysis of the sensitivity of the AEB for the ideal cyclist positioning revealed influencing parameters such as the maximum braking intensity or key parameters of the decision algorithm such as time thresholds and collision distances leading to system response.

The effectiveness of AEB for cyclists has ranged from 35 to 59% for fatalities, 14 to 54% for major injuries, and 11 to 42% for minor injuries.

The AEB system was verified in terms of its efficiency and limitations in the context of cyclists by Zhao et al. [19]. The study analysed images from taxi recorders (40 cases of collisions between a car and a cyclist at an angle of 90°) using the PC-Crash program. Subsequently, the collisions were reconstructed using car models with installed AEB systems and analysed after changing the sensor FOV and the vehicle braking delay time. The results showed that the FOV angle has a significant impact on avoiding a collision between a car and a cyclist. The use of FOV 50° with a braking time of 0.5 s allowed avoiding 6 collisions, and the use of FOV 90° allowed avoiding an additional 14 collisions. Even with the installation of the perfect AEB system providing 360° FOV and no deceleration time, 8 collisions could not be avoided, although the impact speeds were reduced for all

other tested collisions. These collisions were caused by the sudden appearance of a cyclist in front of the car, and the time to collision (TTC) of the cyclist was less than 0.9 s. AEB systems were, however, still effective in mitigating the effects of collisions that occurred due to delayed driver response. Since cyclists are driving at higher speeds, the wide-angle FOV effectively reduces the number of car collisions with cyclists at intersections. Reducing the deceleration time may reduce the number of collisions that are close to the braking performance limit. Collisions that were not avoided, even when the ideal AEB system was used in the PC-Crash simulation, indicate that such collisions can still occur with the participation of autonomous cars if the traffic environment remains unchanged.

The aim of another study [20] evaluating the effectiveness of the AEB system was to show the position of pedestrians and cyclists 3 s before colliding with a vehicle. 175 pedestrian accidents and 127 crashes with cyclists were analysed for this purpose. More cyclists were scattered sideways than pedestrians (90% of cyclists within a radius of about $\pm 80^\circ$, versus $\pm 20^\circ$ for pedestrians), but their distance from the striking vehicle in the 3 s before the collision was not greater (90% of cyclists within 42 m versus 50 m for pedestrians). These data are in line with the higher proportion of slow-moving vehicles involved in accidents with cyclists. The result is that AEB systems for cyclists require almost a full 180° side view, but do not need a greater range than for pedestrians.

Hamdane et al. [21] assessed the effectiveness of the AEB system in pedestrian protection. By analysing actual pedestrian crashes ($N = 100$) taking into account the interactions between the vehicle, the environment, and the pedestrian, an AEB system based on a pedestrian detection camera sensor was modelled to identify the functionality of its various attributes within the timeline of each accident scenario. These attributes were evaluated to determine their impact on pedestrian safety. The process of object detection and activation of the AEB system was studied by changing the sensor's FOV and the delay level. It has been estimated that an FOV of 35° is required to detect and respond to most accident scenarios. It takes 0.5–1 s for the system to react (from the detection of a hazard to the activation of the brakes). In relation to the time remaining until the collision, the authors indicate that about 60% of the pedestrians are visible through sensors with FOV above 35° for 2.5 s before the impact. As the number of visible pedestrians remain fairly similar for the upper FOV, the optimum FOV of the camera seems to be above 35°. This optimized FOV is expected to detect over 80% of hazards, 1 s before the impact.

Regarding the distance left to the collision, it can be emphasized that for all fields of view, more than half of the pedestrians are visible 20 m before the collision, which makes them detectable. The FOV variation plays a major role only in the last 20 m before the collision, better visibility/detectability with a wider FOV. As mentioned before, an angle of 35° seems optimal. Only 10% of the pedestrians are visible 40 m before the collision. It is also found that 10% of the pedestrians are never visible, even with an FOV above 35°. The authors report that about 10% of the pedestrians remain undetected until the accident. This is mainly due to the location of the pedestrians outside the sensor's line of sight.

A study by Ohlin et al. [22] on the effectiveness of the AEB system (AEB city – cars equipped with AEB at low speed) in preventing collisions with pedestrians or cyclists showed that the system is 70% effective in reducing the number of accidents with pedestrians and cyclists.

In Poland, there is a lack of investigation and a gap in knowledge analysis of the effectiveness of driver assistance systems in the context of VRU safety. For this reason, a research experiment was designed at the Motor Transport Institute to evaluate the effectiveness and identify the limitations of currently available driver assistance systems designed to respond to VRU. The AEB system was selected for the tests to verify the response of the driver assistance system in the vehicle to VRU. As indicated earlier, the vast majority of accidents involving VRU occur in urban areas, at low speeds, at pedestrian crossings. The subject pedestrian and cyclist protection research designed by ITS scientists were intended for the urban infrastructure. The TTC at the time the system issued a warning and the distance to the object after stopping the vehicle were analysed.

3 Research methodology

Based on theoretical implications, the following research hypotheses were made:

1. Vehicles equipped with a pedestrian and cyclist recognition module, at speeds of up to 30 km/h, should autonomously attempt braking and warn about the possibility of a collision.
2. The effectiveness of the system depends on the location of the obstacle.
3. In a situation where the pedestrian is standing outside the road (not in the colliding position) on the outer side of the curve, the AEB system should not issue a warning and be activated.

4. Stopping the vehicle at a safe distance from the obstacle is possible with early detection of the object and high braking intensity.

For the purposes of the study, it was necessary to provide high-class mannequins imitating humans. A static pedestrian dummy (Figure 5) and a cyclist dummy (Figure 6) were used for the project. Their construction had to be light enough not to damage the test vehicles and their sensors, and durable enough not to be damaged by the vehicle in a critical situation, allowing them to be reused. A light, foam structure with pneumatic elements for all the components, minimizes the risk of damaging the car body in the situation of incorrect operation of the safety systems.

The research was conducted on the test track in Ułęż, using five selected models of popular passenger car brands offering integrated driver assistance systems in the field of avoiding and reducing the effects of incidents involving VRUs. Test runs took place on the asphalt surface of the track with a length of 5 km. For the purposes of the research experiment, horizontal and vertical markings were placed on one of the lanes, 1,400 m long and 15 m wide (Figure 7).

To perform the measurements in the vehicle system response tests, a measurement data acquisition system was used. Its most important feature is the integrity and the possibility of full synchronisation of the measurement data from acceleration sensors together with the

Figure 5: Pedestrian dummy. Source: “authors” own sources.

Figure 6: Cyclist dummy. Source: “authors” own sources.

data from cameras, microphones, and location sensors. In addition, a measurement data acquisition system, thanks to wireless communication between the two test units, also makes it possible to fully synchronise sensor data from two different vehicles. The entire system consists of, among others, a data recorder, acquisition module, microphone, accelerometers, and cameras. Thanks to this, it is possible to record video and sounds as well as speed, acceleration, and deceleration measurements.

The AEB has undergone a series of tests to check for unusual but probable incidents where it should operate. These situations were selected based on an analysis of the literature presented above as well as observed traffic accidents, which indicated the unusual behaviour of the

vehicles and systems (including lack of response) to real traffic situations. For the purposes of the study, four research scenarios were prepared, varying the location of the obstacle. In one scenario, the response to an obstacle that interferes with the vehicle path (placed in the middle of the line) was tested. The study also tested vehicle reaction for an obstacle that did not collide with the vehicle. In the study, a static pedestrian dummy and cyclist dummy were used as obstacles and, in the experiment on the test track, the driving was done by two trained test drivers whose task was to perform strictly defined manoeuvres (in a repeatable manner in subsequent vehicles) according to previously prepared research scenarios.

The tests conducted for the autonomous braking system included the following:

- Test 1. Driving on a straight road. Static dummy of a pedestrian standing on the road, interfering in the car’s route.
- Test 2. Driving on a straight road. Static dummy of a cyclist standing on the road, interfering in the car’s route.
- Test 3. Driving in a curve. A static model of a pedestrian standing on the road, interfering in the car’s route, on the inside of the curve.
- Test 4. Driving in a curve. A static model of a pedestrian standing off the road (not interfering) on the outside of the curve.

The radius from the centre of the circle defining the arc to half the width of the lane on which the test vehicle was travelling is $R = 23.75$ m.

In order to make the measurements, the scenario was repeated several times for each of the selected combination of obstacle and its position for each vehicle. Due to the differences in the operation of the AEB system, each

Figure 7: View of the test track. Source: “authors” own sources.

Figure 8: Research scheme. Source: “authors” own research.

time, after changing the vehicle, the driver started the test drive by covering the initial section of at least 2–3 min, which was the time needed to stabilize the track and speed of the vehicle.

The test procedure is shown in Figure 8.

A dummy imitating a pedestrian standing perpendicular to the lane direction was placed on a straight section of the road, sideways to an oncoming vehicle. The lanes were 3.5 m wide. The centre of the dummy was 5.25 m from the left edge of the road and 1.75 m from the edge of the lane.

The dummy was in the path of the vehicle’s movement. The driving speed for the test was 9–20 km/h. The dummy was standing still. The test covered the time of detection and type of information for the driver regarding the obstacle as well as information about when braking was initiated after an obstacle was detected, and the vehicle deceleration (Figure 9).

The mock-up with the dummy imitating a cyclist driving perpendicular to the lane direction was placed on a straight section of the road lane, sideways to an oncoming vehicle. The dummy was in the path of the vehicle’s movement. The driver of the vehicle accelerated to a certain speed (between 10 and 26 km/h) and maintained it after stabilizing. The mock-up was standing still.

The test covered the time of detection and the type of information for the driver regarding the obstacle as well as information about when braking was initiated after an obstacle was detected, and the vehicle deceleration (Figure 10).

The dummy imitating a standing pedestrian was set at the left edge of the curve in the road, parallel to the lane direction, sideways to an oncoming vehicle. The centre of the dummy was on the inner edge of the curve in the road – 3.5 m from the left edge of the road. The dummy was in the path of the vehicle’s movement. The driver accelerated to a certain speed (between 10 and 25 km/h) and, after stabilizing, maintained that speed. The dummy was standing still. The test covered the time of detection and the type of information for the driver regarding the obstacle (Figure 11).

The dummy imitating a standing pedestrian was positioned at the right-hand edge of the curve in the road, parallel to the lane direction, facing front or back to an oncoming vehicle. The centre of the dummy was located on the outer edge of the curve in the road – 7 m from the left edge of the road.

The driver accelerated to a certain speed (between 23 and 58 km/h) and, after stabilizing, maintained that speed. The dummy was standing still. The test covered the time of

Figure 9: Research situation in test 1. Source: “authors” own research.

Figure 10: Research situation in test 2. Source: “authors” own research.

Figure 11: Research situation in test 3. Source: “authors” own research.

Figure 12: Research situation in test 4. Source: “authors” own research.

detection and the type of information for the driver regarding the obstacle (Figure 12).

Measured indicators:

TTC – determines the time until a collision of two vehicles if their speeds and trajectories remain unchanged. In

the literature, the TTC is also used to define the relationship between a vehicle and any other object (e.g. a pedestrian). In general terms for this definition, vehicles do not have to move along the same lane or in the same direction; however, for the parameter measured in the tests performed, the same conditions were adopted which characterise the following distance [23] (Figure 13).

The formula which could be used to compute TTC is:

$$TTC = \frac{d}{V_{rel}} \text{ (s)},$$

where d – distance to the vehicle in front (m) and V_{rel} – difference in velocity between the vehicle in front and the following vehicle (m/s).

4 Results

In scenarios 1–3, 44 trials were made.

26 trials (59%) resulted in vehicle braking. In these cases, the response was as expected. Collision warnings were issued in 28 cases.

The obstacle (pedestrian/bicycle dummy) in 29 trials (65.9%) was located on a straight road, and in 15 cases (34.1%), on a collision curve.

In 31 trials (70.5%), a pedestrian model was used, and in 13 trials (29.5%), a cyclist model was used.

Statistically significant differences were observed between the effectiveness of the AEB system depending on the type of obstacle (Kramer’s Phi and V values were 0.438 for a significance level of $P = 0.004$).

A similar tendency was noticed in the case of the efficiency of the system operation and the type of vehicle (Kramer’s Phi and V values amounted to 0.453 for a significance level of $P = 0.061$).

Figure 13: TTC – interpretation source: “authors” own research.

Figure 14: Reactions of the AEB system in the individual scenarios. Source: “authors” own study.

Also, the differences in the way the system reacted depending on the location of the obstacle turned out to be statistically significant (the value of Phi was -0.490 and Kramer’s V was 0.490 for a significance level of $P = 0.006$).

In scenario 1, the vehicle braked in front of the dummy 11 times (69%) out of 16 attempts. A warning was generated in 4 of 5 attempts where automatic braking did not take place. Only in one case out of 16 attempts (6.25%), did the vehicle not brake or warn against a collision.

In the second scenario, there was no automatic braking or a collision warning signal in only one attempt. In the remaining 12 runs, there were both a collision warning signal and automatic braking.

Vehicles performed the worst in scenario 3. Only one vehicle (on three occasions) correctly detected the obstacle and braked in front of it. In two cases, despite the lack of braking of the vehicle, a collision warning was issued, while the remaining ten attempts

Figure 15: Distribution of trials in the individual scenarios. Source: “authors” own study.

Table 1: The number of trials

Vehicle	Number of trials	(%)
A	7	15.9
B	9	20.5
C	9	20.5
D	10	22.7
E	9	20.5
Total	44	100.0

Source: “authors” own research.

Table 2: System reactions depending on the obstacle used

Type of the obstacle used	No reaction	Proper reaction	Total
Pedestrian	17	14	31
Cyclist	1	12	13
Total	18	26	44

Source: “authors” own research.

Table 3: System reactions in each vehicle

Vehicle	No reaction	Proper reaction	Total
A	6	1	7
B	4	5	9
C	4	5	9
D	2	8	10
E	2	7	9
Total	18	26	44

Source: “authors” own research.

ended with no response from the vehicles. The results are shown in Figures 14 and 15.

In scenario 4, the system, as expected, should not detect the pedestrian dummy, i.e. it should not respond to a collision warning signal, nor should it brake itself. Out of 17 attempts from the system, 16 proved to be correct.

In the next step, the TTC was analysed when the system issued a warning signal. Tables 1–4 omit the vehicle number on which the test was performed.

In scenario 1, a pre-collision alert occurred in 15 out of 16 trials. The data from three trials on the timing of issuing a warning signal by the system was lost, so 12 cases where a warning signal occurred were analysed. TTC from when the warning was generated are presented in Table 5.

Analysing the above data, it can be seen that in this scenario, an audible warning sounded in almost all tests

Table 4: System reaction depending on the obstacle location

Obstacle location	No reaction	Proper reaction	Total
Straight road section	5	11	16
On the curve	12	3	15
Total	17	14	31

Source: “authors” own research.

before the collision and then an additional visual message appeared on the dashboard. In only one attempt did both warnings appear simultaneously. The time to a collision, in this case, was very short, 0.2 s. The TTC median at the time the audible warning sounded was 1.15 s in scenario 1. In two cases, this value was extremely low, at 0.2 s. The maximum value of the TTC with the audible warning was 1.7 s. For visual warnings, these values were lower and amounted to 0.85 s for the median, being 0.2 s for the minimum value and 1.2 s for the maximum value.

In scenario 2, the situation was similar. In all of the 12 analysed trials, the audible message sounded before the visual one. The median time to a collision at the time of the audible signal was 1.2 s in scenario 2. The minimum value of the time to a collision was 0.6 s and

the maximum was 1.2 s. The data obtained in scenario 2 are presented in Table 6.

Table 7 summarizes the results for the trials in scenario 3, where a warning was generated. In scenario 3, the audible warning sounded in just 5 out of 15 attempts. In 4 of these cases, the time to a collision was very short (from 0.1 to 0.5 s), and in one trial it was 1 s.

In the next step, the distance to the object after deceleration of the vehicle, and the deceleration level for individual trials were analysed. Only successful trials with automatic braking of the vehicle were taken into account. Trials 1–11 were performed in scenario 1, 12–23 in scenario 2, and 24–26 in scenario 3. Figure 16 shows the distance to the object (pedestrian or cyclist) after deceleration of the vehicle. Figure 17 shows the maximum values of deceleration level obtained in the individual trials.

In three trials, the distance to the dummy was very small. In trials 1 and 26, it was only 20 cm, and in trial number 24, it was only 40 cm. In trial 25, despite the high braking coefficient (above 10 m/s^2), the vehicle stopped only 5 cm in front of the dummy. For trial 3, the data on the distance at which the vehicle stopped were lost. In the remaining trials, these distances were much greater; in 16

Table 5: Time to the collision from when a warning was issued in the individual trials for scenario 1

		Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	Trial 8	Trial 9	Trial 10	Trial 11	Trial 12
TTC (s)	With the audible warning	1.1	0.5	1.3	1.3	1.4	0.2	0.8	0.7	1.2	1.7	1	1.4
	Visual info	0.9	0.3	1.2	1	1.2	0.2	0.5	0.5	0.6	1.1	0.8	1.1

Source: “authors” own research.

Table 6: Time to a collision when a warning sounded in the individual trials for scenario 2

		Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	Trial 8	Trial 9	Trial 10	Trial 11	Trial 12
TTC (s)	With the audible warning	1.1	1.2	1.2	1.2	1	1.3	0.7	0.6	0.6	1.5	1.6	1.6
	Visual info	1	1.1	1.1	1.1	0.8	1.1	0.6	0.5	0.5	1.1	1.2	1.2

Source: “authors” own research.

Table 7: Time to a collision when a warning was issued in individual trials for scenario 3

		Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
TTC (s)	With the audible warning	0.1	1	0.5	0.5	0.4
	Visual info	0	0.8	0.3	0.5	0.4

Source: “authors” own research.

Figure 16: Distance to the object after deceleration of the vehicle in the individual trials. Source: “authors” own research.

trials, they ranged from 0.9 to 2 m, and in 5 cases, even over 2 m. When analysing the results for individual vehicles, differences in the operation of the systems can be noticed. According to the results obtained, the time to a collision at which the first warning for the driver sounded (audible) was between 1.5 and 1.7 s maximum in one of the vehicles. One vehicle was characterized by extremely late warnings. In some trials, the warnings occurred only 0.5–0.8 s before a potential collision. In the remaining vehicles, these values ranged from 0.9 to 1.5 s. The differences were also visible in the braking rate and distances to the object after the deceleration of the vehicle. One

vehicle was characterized by a low braking rate (from 3.5 to 5.1 m/s²) and a long distance to the object. This results in a high level of comfort and safety for both the driver and passengers. In the vehicles characterized by extremely late warnings, the maximum value of the braking rate was much higher and even reached 12.2 m/s². Although, in most cases, the vehicles braked before the obstacles, even with a late reaction by the system, so hard braking within a short time can cause discomfort to the driver and passengers. Additionally, in these cases, short distances from the object were noticed after the vehicle was stopped. The data are presented in Tables 8 and 9.

Figure 17: Maximum values of deceleration level. Source: “authors” own research.

Table 8: Summary of the results for trials with a high value for the braking rate

Trial number	Type of message/warnings	V_1 (m/s)	Distance to the obstacle at the time of the message (m)	TTC at the time of the message (s)	Distance from the obstacle after braking (m)	Delay (m/s^2)
1	Audible	4.81	3.7	0.8	1.3	12.2
	Visual info	3.58	1.8	0.5		
2	Audible	4.31	3.1	0.7	1.1	11.2
	Visual info	3.47	1.6	0.5		
3	Audible	2.61	1.3	0.5	0.4	10.3
	Visual info	2.58	0.8	0.3		
4	Audible	4.08	2	0.5	0	11.2
	Visual info	4.08	2	0.5		
5	Audible	7.11	3	0.4	0.2	11.5

Source: “authors” own research.

Table 9: Summary of results for trials with a low value for the braking rate

Trial number	Type of message/warnings	V_1 (m/s)	Distance to the obstacle at the time of the message (m)	TTC at the time of the message (s)	Distance from the obstacle after braking (m)	Delay (m/s^2)
1	Audible	3.03	3.9	1.3	2	3.1
	Visual info	2.75	3.3	1.2		
3	Audible	4.08	4.6	1.1	1.3	3.8
	Visual info	3.81	3.7	1		
4	Audible	2.58	3.1	1.2	1.6	3.5
	Visual info	2.28	2.6	1.1		
5	Audible	4.31	5.1	1.2	1.9	3.4
	Visual info	3.92	4.3	1.1		
6	Audible	6.14	7.4	1.2	2.1	5.1
	Visual info	5.61	6	1.1		
7	Audible	3.44	3.6	1	1.4	5.5
	Visual info	3.39	2.7	0.8		

Source: “authors” own research.

In scenario 4 – out of 17 tests of the system, 16 turned out to be correct, i.e. the system did not respond to the transmission of a collision warning, nor did it brake automatically. In one trial, the system issued a warning.

Due to the uneven distribution of the variables (no normal distribution), analyses were performed using the Spearman’s rho test. The correlations are presented in Tables 10–15 below.

5 Discussion of the results

The analyses conducted in this study lead to the conclusions that can have a real impact on the issue of road safety. The research presented demonstrated that vehicles equipped with a pedestrian and cyclist recognition module do not always respond as intended and as expected by

the driver. In the conducted tests, where the speed of vehicles ranged between 9–25 km/h, out of 44 trials, braking occurred in only 26 (59%), and a total of 28 trials (64%) had a collision warning. These results partially confirm hypothesis 1, which postulates that “Vehicles equipped with a pedestrian and cyclist recognition module, at speeds of up to 30 km/h, should attempt braking and warn about the possibility of a collision.”

The presented results also support hypothesis 2: “The effectiveness of the system depends on the location of the obstacle.”

Considering the placement of the dummy (straight section of the lane, left edge of the curve in the road parallel to the lane direction, and the right-hand edge), visible differences can be noted in both the response and effectiveness of different vehicles.

On the straight section, both dummies were correctly detected in most cases. In total, for scenarios 1 and 2, the

Table 10: Correlation of distance to the obstacle after braking with the rest of the parameters

Parameters	Correlation coefficient
Braking intensity	0.788**
TTC (when sound occurs)	0.747**
TTC (when visualisation occurs)	0.720**
Vehicle speed at the time of the audible message	0.716**
Vehicle speed at the time of the visual message	0.756**

**Correlation significant at the level of 0.01 (two-sided). Source: “authors” own research.

Table 11: Correlation of braking intensity with the rest of the parameters

Parameters	Correlation coefficient
Distance to the obstacle after braking	0.788**
TTC (when sound occurs)	0.536**
TTC (when visualisation occurs)	0.459**
Vehicle speed at the time of the audible message	0.700**
Vehicle speed at the time of the visual message	0.476**

**Correlation significant at the level of 0.01 (two-sided). Source: “authors” own research.

vehicles braked in approx. 80% of the trials, and in 93% of the trials, a collision warning was issued. On the other hand, the vehicles had a significant problem with detecting a pedestrian on the curved section, with only one out of five vehicles braking in front of the pedestrian in this situation. The tests for this vehicle were done three times, each time the car braked and warned of a collision. Nevertheless, the warnings were generated very late, in

Table 12: Correlation of TTC (when sound occurs) with the rest of the parameters

Parameters	Correlation coefficient
Distance to the obstacle after braking	0.747**
Braking intensity	0.536**
TTC (when visualisation occurs)	0.859**
Vehicle speed at the time of the audible message	0.708**
Vehicle speed at the time of the visual message	0.794**

**Correlation significant at the level of 0.01 (two-sided). Source: “authors” own research.

Table 13: Correlation of TTC (when visualisation occurs) with the rest of the parameters

Parameters	Correlation coefficient
Distance to the obstacle after braking	0.720**
Braking intensity	0.459**
TTC (when sound occurs)	0.859**
Vehicle speed at the time of the audible message	0.722**
Vehicle speed at the time of the visual message	0.790**

**Correlation significant at the level of 0.01 (two-sided). Source: “authors” own research.

Table 14: Correlation of vehicle speed at the time of the audible message with the rest of the parameters

Parameters	Correlation coefficient
Distance to the obstacle after braking	0.716**
Braking intensity	0.700*
TTC (when sound occurs)	0.708**
TTC (when visualisation occurs)	0.722**
Vehicle speed at the time of the visual message	0.824**

**Correlation significant at the level of 0.01 (two-sided). Source: “authors” own research.

each case no more than 0.5 s before a collision, and the braking initiated by the vehicle was very violent. The braking rates were 10.3, 11.2, and 11.5 m/s². Despite such high values, due to the late reaction, the vehicle stopped at a distance of 0.2, 0.05, and 0.4 m, respectively, from the object. Two vehicles issued single collision warnings. The remaining attempts (67%) ended with no reaction from the vehicles. The scenario 4 results confirm hypothesis 3: “In the case of a pedestrian standing outside the road (not interfering) on the outside of the

Table 15: Correlation of vehicle speed at the time of the visual message with the rest of the parameters

Parameters	Correlation coefficient
Distance to the obstacle after braking	0.756**
Braking intensity	0.476*
TTC (when sound occurs)	0.794**
TTC (when visualisation occurs)	0.790**
Vehicle speed at the time of the audible message	0.824**

**Correlation significant at the level of 0.01 (two-sided). Source: “authors” own research.

curve, the AEB system should not issue a warning and be activated.” As expected, the vehicles did not respond to the object when located outside their trajectory, while driving on the curve in the road.

Referring to the 4th hypothesis, it was noticed that early information about a possible collision and thus early braking attempts by the vehicle, resulted in a stop at a relatively large distance from the object (from 1.3 to 2.1 m), despite relatively low levels of deceleration. This data is presented in Table 5. Relatively high values for the braking rates were observed in the presented tests; in the literature, the most common value is about 6 m/s^2 [24,25] and much higher rates can be seen in the analysed cases, for example, in scenario 1, the braking rate was lower in only one trial and amounted to 3.2 m/s^2 , whereas in the others, it ranged from 6.1 to 12.2 m/s^2 . A similar description of such high braking rates can be found in the publication by Ondruš et al. [26]. Measurements were also made for ambient temperatures about 20°C and similar vehicle parameters. In this study the results ranging from 9.3 to 10.89 m/s^2 . However, it should be noted that the tests were conducted at much higher speeds, and despite being of great importance for traffic safety, high deceleration levels caused discomfort for both the driver and the passenger. In scenario 2, slightly lower delay values were observed, where in 5 out of 12 trials, this was lower than 6 m/s^2 ; however, the vehicles stopped at a distance of 1 to 2.1 m from the dummy.

Vehicles that detected objects late had to brake with great intensity in order to prevent a collision. This often resulted in the vehicle stopping very close to the dummy. Such action may cause discomfort and a sense of danger as well as leading to the user distrusting the system, from this perspective, so the refinement of the system and the possibility of early detection of a potential collision seem crucial.

According to the information provided in the vehicle manuals, the system, described as working properly, has many limitations related to the technology used and the lack of redundancy for cameras. Lack of redundancy for cameras is an important shortfall because an AEB system designed to detect and protect pedestrians and cyclists – unlike AEB which only detects vehicles – relies heavily on image analysis. Some instructions clearly state that the system does not detect pedestrians over 2 m tall or when they are in a bent or crouched position. The systems also have a problem with classifying fast-moving objects, such as a running pedestrian or a fast-moving cyclist. Pedestrians obscured by an umbrella or oversized clothing may also be incorrectly classified and, therefore, may not be detected by the vehicle’s vision system. There

are also problems with detecting people and cyclists whose clothing does not differ much in colour from the surroundings. Another issue is the sensitivity of the cameras to dynamic changes in lighting and thus their “glare.”

In the presented research, a dummy of a pedestrian and cyclist were used, both of which were motionless during the tests. The dummies were clearly visible, readily distinguishable from the surroundings. Their dimensions did not exceed the values that should be recognized by the AEB system. The vehicles participating in the study were equipped with a pedestrian detection system. Despite this, the systems responded as expected only in about 60% of the trials.

Notwithstanding the fact that in many of the AEB system tests, the system did not attempt to brake, it did inform the driver by means of a visual and an audible signal about the possibility of a collision. The icons and messages/warnings that appeared on the display had the following content: “Collision warning,” “Attention collision,” “Emergency braking,” “Emergency braking complete,” “Brakes!,” and “Take over steering.”

Despite the many inadequate reactions by the system (e.g. the car slowed down, detected an obstacle, but still hit it) or the lack of reaction, it is not possible to clearly indicate the causes of the system failure. In the observations, it was noted that the operation of the system may depend on the angle of incidence of the light and the lighting conditions of the test vehicle and the obstacle.

Despite these factors, some randomness in the operation of the system was observed. The system was able to react completely different to exactly the same situation (the same scenario and speed) in different vehicles in individual trials. This concerned both the method of reaction and the conditions which led to this reaction.

The presented research results suggest that it is necessary to conduct further research in this area, taking into account the various factors discussed herein.

Safe implementation of highly automated vehicles will be possible after building appropriate competences, awareness, and acceptance of current and future users. For this purpose, it is necessary to conduct social campaigns, reliable advertising campaigns as well as extensive training of drivers ensuring access to knowledge.

6 Conclusion

The analyses show that solutions such as AEB have a chance to increase the level of road safety only if they

are refined and properly used. It should be noted that these systems only support the driver and, contrary to much of the advertising, do not act as a replacement. The results of the analyses show that AEB systems are not able to replace the driver in every situation, and the appropriate reaction to the dynamically changing road situation may be beyond the scope of its capabilities. In this context, the users' awareness of the actual system capabilities and the knowledge of the need to maintain constant control over the vehicle is extremely important. Therefore, the human factor still remains the main element influencing road incidents. Changing this state and enabling the safe implementation of highly automated vehicles will be possible only after building appropriate competences, awareness, and acceptance by current and future users. For this purpose, it is necessary to conduct social campaigns, reliable advertising campaigns as well as extensive training of drivers ensuring access to the knowledge.

In order to ensure a proper understanding of the messages sent to the driver, it is important to ensure that they are properly displayed. Icons and messages should be of an appropriate size and in legible form so as not to create any additional distraction for the driver while in the act of driving. A driver focusing on the dynamic road situation is unable to receive and interpret certain signals correctly, therefore, consideration should also be given to diversifying the stimuli by introducing vibrations or audible signals. This will have a significant impact on the level of road safety, due to the shorter reaction time of the driver and the lack of a need to look away from the road.

Particular attention should be paid to the accuracy of the records in the vehicle manuals and emphasizing the responsibility of the driver, mainly in the context of limitations imposed on the system and situations in which the system does not work effectively.

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