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ENHANCING ROAD SAFETY FOR VULNERABLE ROAD USERS – THE ROLE OF AUTONOMOUS EMERGENCY BRAKING SYSTEMS

Summary. Vulnerable road users are the largest group of road accident victims in the world. At the same time, it should be noted that most road accidents are caused by the motor vehicle driver. An opportunity to increase the level of road safety is emergency braking systems installed in vehicles. Their task is to detect the risk of a collision with another object, issue a warning to the driver and, in the absence of reaction, perform emergency braking. The publication presents the results of research conducted by the Motor Transport Institute as part of the PEDICRASH project. As part of the work, a series of tests of the autonomous emergency braking system were carried out to check unusual but probable cases of events in which it should work. The tests were carried out in a closed area using a few selected models of popular passenger car brands. An additional data acquisition system and dummies imitating vulnerable road users: pedestrians and cyclists were used. The constructions represent the silhouette of an adult person and meet the requirements of the Euro NCAP AEB Protocol. The time of the collision at the time of issuing a warning to the driver was analyzed. Assuming that the vehicle was moving uniformly, the distance from the obstacle was calculated at the time of issuing the warning and after the driver's reaction time (0.7 s and 1 s were assumed) from this signal. The deceleration necessary to brake the vehicle was calculated and it was determined whether the driver would have a chance to brake the vehicle before a pedestrian or a cyclist in a given situation. For cases in which the driver would not be able to brake in time, the speed of the vehicle with which it would hit the vulnerable road users was calculated. Possible injuries and accident costs were then estimated.

1. INTRODUCTION

The World Health Organization estimates that, each year more than 1.3 million people worldwide are killed in road traffic accidents. The number of injured people ranges between 20 and 50 million [1]. There are fewer accidents in the European Union than in other countries. Nevertheless, according to a European Eurostat report, 757,566 crashes resulting in injuries or death in the EU, UK, and EFTA countries were reported in 2020 [2]. This represents a decrease of 22% compared to 2010, which is still unsatisfactory to the goal that was assumed: "halving the overall number of road deaths in the European Union by 2020 starting from 2010 and moving as close as possible to zero fatalities in road transport by 2050."

Long-term changes in the number of road fatalities in the EU 27 countries and three EFTA countries show a 37% decrease in 2020 compared to 2010. Despite this fact, in the European Union, 19,823 people

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lost their lives on roads in 2021 [2]. Regardless of a decrease in the number of accidents causing injuries and fatalities of 39% in 2020 compared to 2010 [1], Poland is still at the top of the countries with the highest number of road accidents and their victims in Europe. It should also be noted that the significant decrease in the number of accidents and people injured in recent years was affected by the pandemic, which caused a reduction in the number of trips.

On average, about 3,000 people die on Polish roads each year. About 40% of the victims are vulnerable road users (including pedestrians, cyclists, and motorcyclists). In 2021, 22,816 road accidents were reported to the police, in which 2,245 people died and 26,415 were injured (8,276 seriously) [3]. In Germany, Italy, and France, the numbers of road fatalities were higher than in Poland. However, these countries have much larger populations, and consequently, the number of fatalities per million inhabitants is much lower than in Poland. The values of this coefficient in Italy and France are very close to the EU average; in Germany, it is almost 30% lower. The number of fatalities per million inhabitants in Poland is 1.5 times higher than the average in the European Union [3].

Vulnerable road users account for a high proportion of victims across Europe. According to an ETSC [1] report, more than 51,300 pedestrians lost their lives on EU roads over the period from 2010 to 2018. The report indicates 19,450 cyclist victims in the same period. In 2018, 5180 pedestrians and 2160 cyclists died in road accidents. This constitutes approximately 30% of all accident victims. It can be observed that the most common cause of death among pedestrians (99%) and cyclists (83%) was a collision with motor vehicles. In both groups, the largest number of victims were reported in cases of collisions with passenger cars and heavy goods transport vehicles.

In 2021, 4755 accidents involving pedestrians were recorded in Poland (20.8% of the total), in which 527 pedestrians died (23.5% of the total) and 4304 were injured (16.3% of the total). Events involving them are mainly classified as "running over a pedestrian." Other events in which a pedestrian was injured include, for example, a collision of two vehicles, driving the vehicle onto the sidewalk, driving into the shelter of a public transport stop, hitting a pole or a sign that overturned and hit the pedestrian, or the pedestrian contributed to a road accident without sustaining a bodily injury.

Drivers of passenger cars are responsible for the largest number of accidents and fatalities in accidents involving vulnerable road users. Among accidents in which pedestrians were victims, the most common causes of accidents were failure to give way to pedestrians on pedestrian crossings (2,086 accidents, 62.7% of all accidents involving pedestrians), in which 131 people died (50.4%) and 2029 (63.8%) were injured. Other reasons include "failure to give way to a pedestrian when turning in other circumstances" (382 accidents, 11.5%) and incorrect reversing [3].

It can be noticed that most often accidents involving vulnerable road users occurred in built-up areas. However, the consequences of accidents taking place in non-built-up areas were more severe. Outside the built-up areas, pedestrians are less visible, especially in bad weather due to a lack of road illumination, and the speed of involved vehicles is typically higher. In addition, built-up areas are characterized by shorter travel times for emergency services, which is of key importance for the severity of accidents. The following paper presents research on the potential benefits of autonomous emergency braking (AEB) systems to the safety of vulnerable road users. The capability of such a system to detect vulnerable road users and react was verified. Also, it was checked if the system is capable of informing the driver giving the appropriate time-span for reaction.

The human capabilities of reaction and the assumptions of vehicle physical processes of deceleration were described in Chapter 2, providing general background to the analysis performed in the next chapters. Chapter 3 introduces the methodology of the experiment and the main results. In Chapters 4 and 5, the results and conclusions of the study are presented.

2. HUMAN FACTORS IN ROAD ACCIDENTS

2.1. Driver reaction time

Driver reaction time is a key factor influencing traffic situations, especially accidents, and is responsible for part of the time it takes the car to stop. It has a critical significance for the consequences of an accident while determining the vehicle speed of impact. *Reaction time* 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)".

Taking into account the fact that accidents are most often caused by drivers, an important factor to be analyzed is the driver's reaction time. Reaction time is the time it takes for a system or object to respond to a given signal. Each of the processes related to perception and executive activities (reaction) takes place at a specific time. Thus, the reaction time consists of five partial times.

The reaction time in traffic can be divided into several factors:

- Reaction time.
- The time of arousal in the receptor, which depends primarily on the concentration of attention and the ability to see peripherally.
- The time of transferring the arousal to the central nervous system, which is related to the speed of sensory nerve conduction.
- The duration of the arousal through the nerve centers and the formation of the executive signal. It depends primarily on the mobility of nervous processes and is the longest and most diverse parameter determining the reaction time. It largely depends on the degree of automation of the reaction habit, as well as its plasticity. Training, a high degree of mastering the technique of driving a vehicle, and good coordination of movements contribute to the reduction of this indicator. Thus, through exercise, it is possible to shorten the time.
- The time of the transmission of the signal from the central nervous system to the muscle, which is related to the speed of conduction in the motor fibers.
- The time of muscle stimulation, which leads to a change in its tension and the initiation of movement, is associated with, among others, the strength of muscle groups, as well as movement coordination, the ability to relax muscles not participating in movement. By practicing, it is possible to shorten this reaction time as well.

In traffic psychology, one may find different distinctions in reaction time phases. According to the work of Bałaban [4] the reaction time might be divided into three phases. The work describes results from experimental studies given for 85–95% of the population and analyzing individual phases separately:

- Perception time, which is associated with the perception of the stimulus. Perception time varies due to several sub-factors like the position of the object in the driver's field of view which in traffic might be another participant of the traffic or an obstacle, the contrast between the object and the background, and the relative movement of this object. Perception time ranges from 0–0.7 s.
- The time required to recognize the object and make a decision, which is affected by the performance of other activities (regardless of whether they are driving- or non-driving-related). This time ranges from 0.2–0.6 s.
- Physical reaction, also known as motoric time, which is the interval from the initiation of movement to its end [5]. The start point the moment of initiation of a physical reaction is taken into account, which might occur as a change of tension or muscle stimulation. It differs largely due to a characteristic of the maneuver to be performed but was evaluated from 0.25–0.7 s for braking maneuvers, and 0.2 s for turning.

Basic reaction time may be preceded by peripheral perception time when an obstacle appears beyond the driver's line of sight. When assessing solutions dedicated to protecting vulnerable road users, the benefits and costs associated with installing devices to detect pedestrians and braking autonomously are estimated in order to prevent or reduce speed in the event of a collision with a pedestrian. This aspect was addressed by Edwards et al. [6].

Reaction time depends also on the expectations of the driver and his/her attentiveness. Reaction time is assumed to be 0.5–0.8 s if the driver expects danger and 0.7–0.9 s if they do not expect the danger but drive attentively. Reaction times rise to 1.4–1.9 s [4] if the driver drives the vehicle carelessly. It is generally assumed that the average driver's reaction time to the sudden appearance of an obstacle or object on the road is 0.7–1.0 s, which is based on the results of experimental studies. People with special mental predispositions, when well-rested and concentrated on the task, can shorten this time by about 0.3 s in repeatable measurements.

Table 1

Driver reaction times when braking, depending on the location of the object in the driver's field of vision (concentration) [7]

	Reaction time [s]		
	For 2% of population	Mean	For 98% of population
An obstacle in the field of concentration	0.47	0.84	1.34
The deviation from the central field is 5°	0.79	1.32	0.89
At a deviation of more than 5°	0.88	1.45	2.04

The driver's reaction time also depends on the degree of surprise of the situation (appearance of the stimulus). For 85–95% of the population, the average reaction time values are in the following ranges [5]:

- 0.7–0.9 s in case of a simple event,
- 1.0–1.2 s in case of an expected event,
- 1.3–1.5 s in case of an unexpected event.

As the vehicle speed increases, the share of the reaction time in the total stopping time of the vehicle decreases. Still, at a speed of 130 km/h, it constitutes more than 1/4 (26.6%) of this time. At lower speeds, this share is more significant; at a speed of 40 km/h, it is half of the stopping time. An important element from a psychophysiological point of view that affects reaction time is the efficiency of the nervous system. It enables the reception of stimuli coming from the environment and the transfer of the appropriate response to them.

According to the expected reaction times, the safety systems designed to issue a warning to the driver should provide enough time for a reaction. Otherwise, their use would not provide the expected benefits. The verification of this capability is one of the goals of this article.

2.2. Vehicle deceleration level

In addition to the driver's reaction time, an important factor influencing braking distance is the achievable deceleration level of the vehicle. Different values of this variable can be found in the literature, depending on whether braking is assisted by an emergency braking system or AEB. The research by Nils Lubbe [8] determined the values of drivers' reaction times and the values of drivers' braking coefficients after issuing a warning about a collision with a pedestrian. The publication compares different types of messages (audio-visual, audio-visual-haptic, heads-up display). A driving simulator was used for the tests. The scenario involved driving in city traffic at a constant speed of 30 km/h. In addition, the drivers were given tasks that distracted them significantly. Most of the drivers (90%) exceeded a maximum deceleration of 3.6 m/s^2 and a jerk of 5.3 m/s^3 [8].

In the publication of Anderson et al., 104 accidents were reconstructed to determine the potential effectiveness of the emergency braking system. The results show that when the driver starts braking after receiving a warning, the system increases the braking intensity to the maximum value. The experiment determined the value of the driver's braking intensity at the level of 0.7 g and 0.8 g when braking is assisted by the system [9]. Some manufacturers provide maximum braking up to 1.0 g [10]. The constant g is the acceleration due to gravity, which is 9.81 m/s^2.

Some literature items assume a vehicle deceleration of about 6 m/s^2. This value is used, for example, in tests conducted by NCAP [11]. The NHTSA study [12] presents the results of research conducted on 100 drivers. It was shown that the highest value of the driver's braking deceleration was 0.74 g (7.26 m/s^2) for near-collision situations. For 58% of the tested drivers in this situation, the deceleration level was 0.7 g (6.87 m/s^2). Taking into account the analysis of the above sources, in this paper, calculations were made for two boundary values of the braking intensity: 0.61 g (6 m/s^2) and 0.7 g.

In the literature, a vehicle deceleration of about 6 m/s^2 may also be found. This value is used, for example, in tests conducted by NCAP [13]. The NHTSA study [12] presents the results of research conducted on 100 drivers. It was shown that the highest value of the driver's braking deceleration was 0.74 g (7.26 m/s^2) for near-collision situations. For 58% of the tested drivers in this situation, the deceleration level was 0.7 g (6.87 m/s^2).

Taking into account the analysis of the above sources, in this paper calculations were made for two boundary values of the braking intensity: 0.61g (6m/s^2) and 0.7g.

2.3. Opportunities to increase the level of safety of vulnerable road users – Autonomous emergency braking

Edwards et al. [14] conducted a study to assess the potential benefits of advanced emergency braking systems for pedestrian safety in Europe, specifically focusing on the UK and Germany as representative cases. The analysis covered fatalities as well as severely and minor injured victims. The methodology involved analyzing the impact velocity distribution in pedestrian-car accidents and estimating the potential reduction in fatalities and injuries with the implementation of various types of AEB systems. These systems ranged from currently available ones to future performance-enhanced versions, as well as a reference system representing the best technically feasible option.

In both the UK and Germany, the estimated annual benefits varied depending on the type of AEB system installed, ranging from £119 million to £385 million for the UK and from €63 million to €216 million for Germany. Sensitivity analyses indicated that these estimates could fluctuate significantly based on factors like nighttime operation and assumed road friction, potentially doubling or halving the nominal benefits. By extrapolating these findings to the broader European context, the study estimated that implementing pedestrian AEB systems across all cars in Europe could yield annual benefits ranging from approximately €1 billion to €3.5 billion, depending on the sophistication of the system. To ensure cost-effectiveness, the study suggested that the cost per car for implementing such systems should ideally be less than €80–280 based on the number of new passenger cars registered in Europe each year.

2.4. Accident costs in Poland

When addressing vulnerable road users' safety the main outcome is commonly a decrease in the number of caused fatalities or accidents. A second important factor that is frequently undervalued is a decrease in the severity of the accident. There is no worldwide standard method for measuring the severity of crashes, but in the literature, the Abbreviated Injury Scale (AIS) [15] is frequently used to objectively describe the probability of the effects of accidents in terms of injuries. The AIS provides an internationally accepted tool for ranking injury severity that classifies an individual injury by body region according to its relative severity on a 6-point scale (1 = minor and 6 = maximal). In traffic accidents analysis, the "3+" AIS score (injuries scored from 3 to 6) is normally used to describe severe injuries, which is incorporated in examples in road safety strategies [16] as a reference for injuries in traffic incidents. Some publications provide more in-depth analyses [17] but are not of common use in traffic accident analysis.

AIS3+ is used in several publications [18, 19, 20] to determine the probability model of accident severity depending on the vehicle speed. Besides deficiencies of the impact speed–fatality probability relationships model described in the work of Jurewicz et al. [21], it is broadly accepted and used as a valid model for the simulation of accident effects [22, 23, 24, 25, 26]. The results of some studies show that three factors affect actual accident severity: the impact speed [eg. 27], properties of pedestrians [28,29], and properties of vehicles [30]. However, when modeling the problem, these are commonly generalized to the effect of impact speed. In this chapter, the authors use the AIS3+ model described by Wramborg [16] to assess the potential reduction of accident societal costs due to the use of collision warning systems analyzed in field studies.

In Poland, AIS classification is not commonly used, and there are no sources that refer to injury severity in terms of societal costs of accidents. In line with Polish regulations, and according to commonly accepted methodology, the costs of accidents in Poland are assessed with the willingness-to-pay method applied by Jaździk-Osmólska [31]. A recent report from 2021 assessed individual costs on:

- Fatal – 2.6 mln PLN – ca. 554,000 EUR
- Severely injured – 3.5 mln PLN – ca. 764,000 EUR
- Lightly injured – 51,300 PLN – ca. 11,000 EUR
- Material losses – 4700 PLN – ca. 1000 EUR

In further analyses, it is assumed that severely injured in an accident is adequate to AIS3+ while definitions in both scales are close to each other.

3. EVALUATION OF AEB EFFECTIVENESS

3.1. Method

Studies conducted by the institute on the effectiveness of the AEB system in the context of vulnerable road users are described in the publication by Ucińska and Pełka [32]. This article also includes a detailed description of the system's operation and limitations, as well as an analysis of the research so far. It should be noted that the current level of technological advancement mostly provides support for the driver in performing individual steering activities.

The task of the system is to warn the driver of impending danger and to apply the brakes only in a critical situation. This article presents the results of the analyses carried out in the context of the driver's reaction possibilities in the event of not noticing the danger and receiving a warning from the system.

The research was conducted in a closed test track. Several selected models of popular passenger cars offering integrated driver assistance systems in the field of reducing the consequences of incidents involving vulnerable road users were used. The vehicles in this study were anonymized due to the conditions of the project. The vehicles were equipped with an additional data acquisition system, enabling registration of events (recording of visual and audible warnings inside the cabin) and measurement of vehicle parameters such as speed and exact position. The test runs took place on an asphalt surface with a total length of 5 km. Horizontal and vertical markings were placed on one of the 1400-m-long and 15-m-wide segments.

For the proper performance of the tests, it was necessary to provide high-class mock-ups imitating people. For this purpose, a pedestrian dummy and a cyclist dummy were purchased. Both designs represent an adult person and meet the requirements of the Euro NCAP AEB Protocol [11]. Mock-ups are made of light, foam construction together with the pneumatic elements of all components of the set, minimizing the risk of damage to the car body in the event of incorrect operation of the safety system [33, 34, 12].

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

1. The emergency braking system should detect the risk of a collision with a vulnerable road user and warn the driver
2. An appropriate message (sound, visual) should be issued in time allowing the driver to react.

The AEB system was subjected to a series of tests. Two research scenarios were prepared, differing in terms of the location of the obstacle (reaction to obstacles located in a collision with the vehicle and the type of obstacle): (1) a static pedestrian dummy and (2) a cyclist dummy. In both experiments, the dummies were situated in front of an approaching vehicle, in the middle of the 3.5-m-wide lane. The dummies were static. In the experiment on the test track, the driving tests were conducted by two trained test drivers whose task was to perform strictly defined maneuvers (repeatably in subsequent vehicles) according to previously prepared research scenarios. The drivers performed the tests in a range of permissible traffic speeds, following strict procedures of vehicle speed and driving direction stabilization to guarantee comparability. The tests were performed in the daytime during good lighting conditions and without any circumstances that might affect system performance.

The tests carried out for the AEB included the following:
Scenario 1: Straight road, static pedestrian mockup standing on the road (collision-causing)
Scenario 2: Straight road, static cyclist mockup standing on the road (collision-causing)

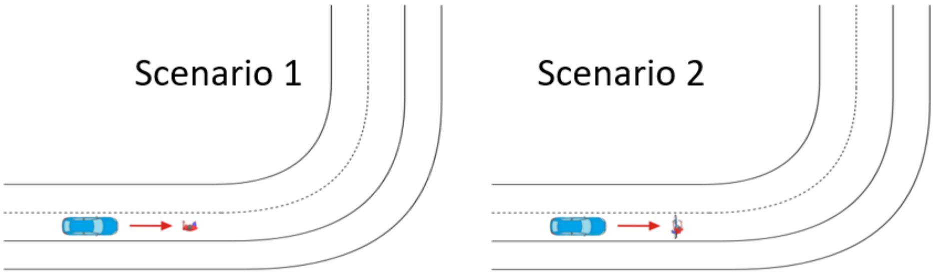

Fig. 1. Test situations for Scenarios 1 and 2

The scenario was repeated several times for each of the selected vehicles. Due to the differences in the operation of the AEB system, each time the driver changed the vehicle, the test run began with covering the initiating section lasting at least two minutes of driving. This was the time needed to stabilize the track and speed. During tests, the drivers stabilized the vehicle speed and lane position on the straight section of about 500 m that preceded the dummy position. The position of the dummy was planned to activate the AEB system in the vehicle during each passing.

3.2. Results

In performing further analysis, the exact speed and position of the vehicle were taken into account based on the GPS-RTK measurement unit. The distance from the obstacle was calculated at the moment of issuing the warning assuming that the vehicle was moving at a constant speed equal to the speed when the audible warning was issued. Also, the calculation of distance after 0.7 and 1 s from this signal was made on this basis. First, the calculations were made for the tests in which the time to the collision was greater than or equal to the shortest reaction time of the driver (i.e., 0.7 s). Then, it was assumed that after the reaction time elapsed, the driver would brake. The values of the achievable inhibition coefficients were adopted based on the literature analysis. Two cases were considered: braking intensity at the level of 6 m/s^2 and 6.87 m/s^2. On this basis, it was calculated whether the driver would have a chance to brake the vehicle and avoid a collision with a vulnerable road user. If the driver did not manage to brake in time, the collision speed was calculated.

For Scenario 1, full data was obtained from 16 trials. In 12 of them, an audible warning was generated, which means that a threat was recognized. It should be noted that the driver's alert generation times varied significantly from one vehicle to another. According to the results presented in Table 2, assuming that the driver's reaction time was 0.7 s and the maximum possible deceleration level was 6 m/s^2, only in three out of 12 (25%) cases would the driver have a chance to brake completely in front of a pedestrian. With a deceleration of 6.87 m/s^2, the collision would not have occurred in four out of 12 attempts (33.33%). In other cases, there would have been a collision with a pedestrian. Depending on the time left for the reaction, the impact speed ranged from 0.32 m/s (1.15 km/h) to even 4.31 m/s (15.52 km/h). For the assumed reaction time of 1 s, only in one case, with the assumed deceleration of 0.7 g (6.87 m/s^2), would the driver be able to brake in front of the pedestrian. In other situations, for both values of deceleration, there would be a collision with a pedestrian. Impact velocities ranged from 0.08 m/s to 4.81 m/s (17.32 km/h).

Tables 4 and 5 show the results for Scenario 2.

In Scenario 2, 13 trials were obtained. In 12 of them, an audible warning was obtained. The results of 12 runs were analyzed. As in Scenario 1, for eight attempts, the time to collision at the moment of the warning occurrence was longer than 1 s, which gave the driver a chance to react. The results of the conducted analyses, therefore, show that the majority of vehicles correctly recognized the pedestrian dummy and took the correct reactions, in line with the driver's expectations.

Table 2

Results for Scenario 1 – Reaction time: 0.7 s

Vehicle	**Message type**	**V1 [km/h]**	**V1 [m/s]**	**Distance [m]**	**Time to collision [s]**	**Distance to collision after 0,7s [m]**	**Deceleration [m/s^2]**	**Collision speed for reaction time 1s [m/s]**	**Deceleration [m/s^2]**	**Collision speed for reaction time 0,7s [m/s]**
A	Auditory	14.2	3.94	4.4	**1.1**	1.64	6	1.54	6.87	1.20
B	Auditory	8	2.22	1	**0.5**	Collision	-	2.22	6.87	2.22
	Auditory	10.9	3.03	3.9	1.3	1.78	6	Collision avoided	6.87	Collision avoided
C	Auditory	9.9	2.75	BD	BD	BD	BD	BD	6.87	2.75
	Auditory	14.1	3.92	5.2	1.3	2.46	6	0.32	6.87	Collision avoided
	Auditory	18.6	5.17	7.4	1.4	3.78	6	0.97	6.87	0.36
D	Auditory	7.1	1.97	0.4	**0.2**	Collision	-	1.97	1.97	1.97
	Auditory	9.6	2.67	BD	BD	BD	-	BD	6.87	2.67
	Auditory	17.3	4.81	3.7	**0.8**	0.34	6	4.21	6.87	4.21
	Auditory	15.5	4.31	3.1	**0.7**	0.00	-	4.31	6.87	4.31
E	Auditory	9.1	2.53	3.1	1.2	1.33	6	Collision avoided	6.87	Collision avoided
	Auditory	15.4	4.28	7.1	1.7	4.11	6	Collision avoided	6.87	Collision avoided
	Auditory	15.6	4.33	4.4	**1**	1.37	6	2.53	6.87	2.27
	Auditory	24.7	6.86	9.9	1.4	5.10	6	2.66	6.87	2.05

Table 3

Results for Scenario 1 – Response time: 1 s

Vehicle	**Message type**	**V1 [km/h]**	**V1 [m/s]**	**Distance [m]**	**Time to collision [s]**	**Distance to collision after 0,7s [m]**	**Deceleration [m/s^2]**	**Collision speed for reaction time 1s [m/s]**	**Deceleration [m/s^2]**	**Collision speed for reaction time 0,7s [m/s]**
A	Auditory	14.2	3.94	4.4	**1.1**	0.46	**6**	3.34	**6.87**	3.26
B	Auditory	8	2.22	1	**0.5**		**6**	2.22	**6.87**	2.22
	Auditory	10.9	3.03	3.9	1.3	0.87	**6**	1.23	**6.87**	0.97
C	Auditory	9.9	2.75	BD	BD	BD	**6**		**6.87**	
	Auditory	14.1	3.92	5.2	1.3	1.28	**6**	2.12	**6.87**	1.86
	Auditory	18.6	5.17	7.4	1.4	2.23	**6**	2.77	**6.87**	2.42
D	Auditory	7.1	1.97	0.4	**0.2**		**6**	1.97	**6.87**	1.97
	Auditory	9.6	2.67	BD	BD	BD	**6**		**6.87**	2.67
	Auditory	17.3	4.81	3.7	**0.8**		**6**	4.81	**6.87**	4.81
	Auditory	15.5	4.31	3.1	**0.7**		**6**	4.31	**6.87**	4.31
E	Auditory	9.1	2.53	3.1	1.2	0.57	**6**	1.33	**6.87**	1.15
	Auditory	**15.4**	**4.28**	**7.1**	**1.7**	**2.82**	**6**	**0.08**	**6.87**	Collision avoided
	Auditory	15.6	4.33	4.4	**1**	0.00	**6**	4.33	**6.87**	4.33
	Auditory	**24.7**	**6.86**	**9.9**	**1.4**	**3.04**	**6**	4.46	**6.87**	4.11

Table 4

Results for Scenario 2 – reaction time: 0,7 s

Vehicle	**Message type**	**V1 [km/h]**	**V1 [m/s]**	**Distance [m]**	**Time to collision [s]**	**Distance to collision after 0,7s [m]**	**Deceleration [m/s^2]**	**Collision speed for reaction time 0,7s [m/s]**	**Deceleration [m/s^2]**	**Collision speed for reaction time 0,7s [m/s]**
A	Auditory	14.7	4.08	4.6	1.1	1.74	**6**	1.68	**6.87**	1.34
B	Auditory	9.3	2.58	3.1	1.2	1.29	**6**	Collision avoided	**6.87**	Collision avoided
	Auditory	15.5	4.31	5.1	1.2	2.09	**6**	1.31	**6.87**	0.87
	Auditory	22.1	6.14	7.4	1.2	3.10	**6**	3.14	**6.87**	2.70
C	Auditory	12.4	3.44	3.6	**1**	1.19	**6**	1.64	**6.87**	1.38
	Auditory	26.5	7.36	9.9	1.3	4.75	**6**	3.76	**6.87**	3.24
D	Auditory	9.3	2.58	1.8	**0.7**			2.58		2.58
	Auditory	12.5	3.47	2.1	**0.6**			3.47		3.47
	Auditory	19.3	5.36	3	**0.6**			5.36		5.36
E	Auditory	10.3	2.86	4.3	1.5	2.30	**6**	Collision avoided	**6.87**	Collision avoided
	Auditory	15	4.17	6.6	1.6	3.68	**6**	Collision avoided	**6.87**	Collision avoided
	Auditory	24.6	6.83	10.7	1.6	5.92	**6**	1.43	**6.87**	0.65

Table 5

Results for Scenario 2 – reaction time: 1 s

Vehicle	**Message type**	**V1 [km/h]**	**V1 [m/s]**	**Distance [m]**	**Time to collision [s]**	**Distance to collision after 1s [m]**	**Deceleration [m/s^2]**	**Collision speed for reaction time 1s [m/s]**	**Deceleration [m/s^2]**	**Collision speed for reaction time 1s [m/s]**
A	Auditory	14.7	4.08	4.6	**1.1**	0.52	**6**	3.48	**6.87**	3.40
B	Auditory	9.3	2.58	3.1	1.2	0.52	**6**	1.38	**6.87**	1.21
	Auditory	15.5	4.31	5.1	1.2	0.79	**6**	3.11	**6.87**	2.93
	Auditory	**22.1**	**6.14**	**7.4**	**1.2**	1.26	**6**	4.94	**6.87**	4.76
C	Auditory	12.4	3.44	3.6	**1**	0.16	**6**	3.44	**6.87**	3.44
	Auditory	26.5	7.36	9.9	1.3	2.54	**6**	5.56	**6.87**	5.30
D	Auditory	9.3	2.58	1.8	**0.7**		**6**	2.58	**6.87**	2.58
	Auditory	12.5	3.47	2.1	**0.6**		**6**	3.47	**6.87**	3.47
	Auditory	19.3	5.36	3	**0.6**		**6**	5.36	**6.87**	5.36
E	Auditory	10.3	2.86	4.3	1.5	1.44	**6**	Collision avoided	**6.87**	Collision avoided
	Auditory	15	4.17	6.6	1.6	2.43	**6**	0.57	**6.87**	0.04
	Auditory	24.6	6.83	10.7	1.6	3.87	**6**	3.23	**6.87**	2.71

However, special attention should be paid to the time to collision in which warnings are generated. Despite the very low speeds of about 9–25 km/h, in the absence of braking from the AEB system, in most cases, the driver would not have a chance to stop in front of a pedestrian. For a reaction time of 0.7 s, only four out of 12 (33.33%) cases would avoid a collision. With a reaction time of 1 s, avoiding a collision would be possible only in one case.

The dataset was analyzed for three variants: (1) when the driver has a reaction time of 1 s, (2) when the driver has a reaction time of 0.7s, and (3) when the system reacts imminently itself.

The results show that for 1 s driver reaction time, 35.7% of samples do not change the result of the incident. For 0.7 s driver reaction time, 28.6% of samples do not give a chance for reaction. For 1 s reaction time, the mean reduction of accident cost is 10,650 EUR, while for 0.7 s it is 27,300 EUR. For the automatic braking system, it is 72,600 EUR.

On the basis of these results, the calculation of the possible impact on the cost of the accidents was calculated. The calculation was made taking into account a possible model of the changes in the characteristic of damage depending on the vehicle speed. For calculations, the unit costs for different events were calculated with the possible probability of their occurrence based on the Polish unit costs of accidents presented in Chapter 2. The results were analyzed for all cases taken in both scenarios, dividing into cases with the 0.7-s reaction time of the driver, and with the 1-s reaction time. Additionally, the case in which the system would not provide the warning but would automatically start braking was calculated. The results of the calculations are presented in Fig. 2.

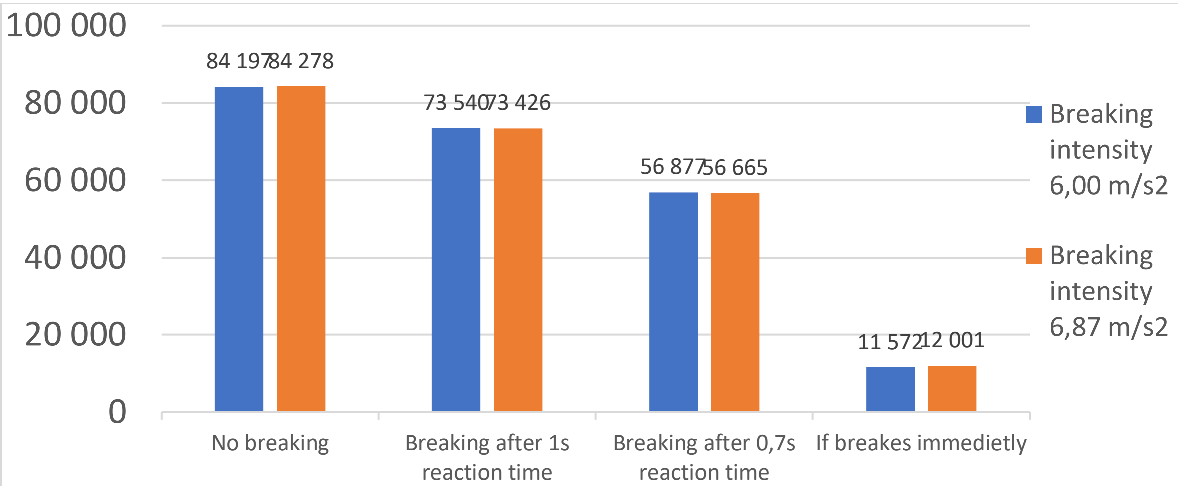

Fig. 2. Comparison of calculations of accident costs for braking intensities of 6.00 m/s^2 and 6.87 m/s^2

The results show the potential change in accident costs due to the use of a collision warning system. The conducted estimations indicate the possibility of reducing the effects—and, thus, the costs—of accidents by 12–16% in the case of the driver's reaction within 1 s, respectively, for the braking intensities of 6.00 m/s^2 and 6.87 m/s^2 and 32–36% in the case of a reaction within 0.7s. This indicates the possibility of obtaining measurable system benefits from the introduction of systems warning about a possible collision. It should be noted, however, that the greatest benefits—between 86 and 89%—would come from automatically braking the vehicle instead of alerting the driver. In near-collision situations, the driver's reaction time is an extremely important factor, which significantly reduces the potential benefits of using the system.

3.3. Results discussion

The following research hypotheses were verified in the publication:

- The emergency braking system should detect the risk of a collision with a vulnerable road user and warn the driver.
- An appropriate message (sound, visual) should be issued in time for the driver to react.

The results show that Hypothesis 1 was supported. In most cases (12/16 in Scenario 1 and 12/13 in Scenario 2), vehicles detected a vulnerable road user and generated a warning.

Hypothesis 2 was rejected. In most cases, the warnings appeared so late that the driver would not be able to brake the vehicle completely.

4. CONCLUSIONS

Despite technological developments, the human factor, including the driver's reaction time and the achievable braking intensity, remain key aspects of the level of road safety. Despite manufacturers' declarations and marketing materials, advanced driver assistance systems do not relieve the driver of their responsibilities. The driver remains responsible for all vehicle controls and road safety. The research findings show that the AEB system did not activate the warning in some cases, which will result in an accident without driver vigilance.

Additionally, despite similar trade names and purposes of usage, the way the systems operate, their sensitivity, and the timing of the driver alert varies significantly from manufacturer to manufacturer. All vehicles were tested in the same conditions, so the influence of weather and road conditions on the test results should be excluded. For this reason, it seems necessary to have broad access to information and sensitize potential users to the way systems operate and their limitations depending on the manufacturer. Currently, most users assume the same operation of systems with similar functionality. Another solution to this issue might be the broad standardization of systems, especially in aspects of the human-machine interface to provide effective and unambiguous communication and minimal circumstances of use (the so-called operational domain). Standardization guarantees the reliable use of systems in predefined conditions that will be understandable to users.

Although the results show significant benefits due to using warning systems and the potential reduction of accident costs of 14–34%, depending on possible driver reaction times on the current state of the advancement, further development of these systems should be provided to maximize these benefits. In the case of autonomous braking, the potential for reductions in accident costs (as well as the overall number of accidents and victims) is much higher (more than 85%). Continuous research and development of vulnerable road users-focused safety systems is also necessary regarding the potential use of fully autonomous vehicles, which will need to perform accordingly in similar traffic situations.

Therefore, currently, only the conscious and safe use of driver assistance systems can reduce the number of road accident victims, especially those involving vulnerable road users. The analyses presented in this publication show that the use of systems detecting vulnerable road users on a large scale will contribute to a significant reduction in the costs of road accidents. Further tests and developments of autonomous braking systems regarding vulnerable road users are necessary to improve their effectiveness and to provide a sufficient level of reliability for automated vehicle use.

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