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ASSESSMENT OF THE INFLUENCE OF THE ADVANCED EMERGENCY BRAKING SYSTEMS ON PEDESTRIAN SAFETY

OCENA WPŁYWU SYSTEMÓW AUTOMATYCZNEGO HAMOWANIA NA BEZPIECZEŃSTWO PIESZYCH

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Summary

The paper presents benefits of application of Advanced Emergency Braking Systems (AEBS) from the pedestrian's safety point of view. The main parameters were the number of undesirable events (running over a pedestrian) and accidents as well as the probability of the pedestrian death or serious injury. The relationship between probability of injury (fatal or serious) and parameters: impact velocity and pedestrian's age was based on statistical data from the literature. Then, using the Monte Carlo method, analysis of the accident-prone situations (1,000 cases for each of the 10 different distances between pedestrian and car) was carried out. Variability of the parameters such as: car's initial velocity, driver's reaction time, braking deceleration, delay in brake activation, time of braking deceleration increase was described with the use of normal or log-normal distributions. Pedestrian's age was presented as a special distribution approximating the population pyramid in Poland. The analysis conducted showed a significant increase of pedestrian safety (decrease in the following parameters: number of undesirable events and accidents, probability of death or serious injury by 40-50%). This paper presents the benefits from the introduction of advanced driver assistance systems on the example of ABES, which are not yet widely used and will be implemented in the future.

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Keywords: road safety, pedestrian safety, Advanced Emergency Braking Systems, Monte Carlo method, aDrive

Streszczenie

Tematem niniejszej publikacji jest przedstawienie korzyści z zastosowania systemów automatycznego hamowania awaryjnego (AEBS) z punktu widzenia bezpieczeństwa pieszego. Za główne parametry uznano liczbę zdarzeń niepożądanych (najechanie na przechodnia) i wypadków oraz prawdopodobieństwo poniesienia śmierci lub poważnych obrażeń przez pieszego. Na podstawie danych statystycznych dostępnych w literaturze prawdopodobieństwo obrażeń (poważnych i śmiertelnych) uzależniono od prędkości zderzenia oraz wieku pieszego. Następnie przeprowadzono analizę metodą Monte Carlo dla sytuacji prowadzących do wypadku (uwzględniono 1000 przypadków dla każdej z 10 założonych odległości pomiędzy pieszym a samochodem). Zmienność parametrów wejściowych takich jak prędkość początkowa samochodu, czas reakcji kierowcy, opóźnienie hamowania, czas zwłoki zadziałania hamulców, czas narastania opóźnienia hamowania została przybliżona za pomocą rozkładów normalnych lub logarytmiczno-normalnych. Wiek pieszego przedstawiono jako rozkład przybliżający piramidę wieku społeczeństwa polskiego. Przeprowadzone analizy wykazały znaczący wzrost bezpieczeństwa pieszego (spadek następujących parametrów: liczby zdarzeń niepożądanych, prawdopodobieństwa śmierci lub poważnych obrażeń o 40–50%). Niniejsza publikacja przedstawia na przykładzie AEBS korzyści z wprowadzenia zaawansowanych systemów wsparcia kierowcy, które nie są jeszcze powszechnie stosowane i będą dopiero wdrażane.

Słowa kluczowe: bezpieczeństwo drogowe, bezpieczeństwo pieszych, zaawansowane systemy automatycznego hamowania, metoda Monte Carlo, aDrive

1. Introduction

Safety analysis is one of the priorities of science in the world. Engineers use many methods and tools for risk and reliability assessment. Development of safety engineering is revealed by the ability to better identify possible hazards, considering safety issues at the design stage of technical equipment and progress in the field of hazard prevention through the extension of existing methods of risk and reliability analysis and proposing new ones [7].

Nowadays, more and more often the cars are equipped with systems helping the driver. These systems called Advanced Driver Assistance Systems ("ADAS") aim to raise road safety. Part of them systems is Advanced Emergency Braking Systems ("AEBS"), whose sensors monitor the proximity of other objects and detect situations that could cause a collision. In such cases, the system will automatically activate brakes to avoid an accident.

In this paper, the influence of the application of AEBS in terms of pedestrian safety will be checked. Based on a change of impact velocity between car and pedestrian, assessment of the reduction of the probability of undesirable events, accidents, death or serious injury will be possible.

2. The assumptions and implemented model for the Monte Carlo analysis

Conducted analysis included a case of running over a pedestrian by a car in an urban environment during a day. The analysis covered the accident-prone situations, those in which the impact (undesirable event) occurs if the driver does not have time to stop the car. It was found that a driver did not turn and a pedestrian's velocity is such that he is on a collision path with the car at the moment of a potential impact.

Variability, randomness and independence of input parameters (car's initial velocity, driver's reaction time, braking deceleration, delay in brake activation, time of braking deceleration increase, pedestrian's age) were assured using Monte Carlo method. This variables (specifically, values of cumulative distribution function) were randomized 1,000 times for each of the 10 different distances (5, 10, 15, ..., 50 m) between pedestrian and car. Normal and log-normal distributions were applied except pedestrian's age, which was presented as a special distribution approximating the population pyramid in Poland.

The impact velocity (if it occurred) was calculated for two variants:

- Car was not equipped with AEBS,
- Car was equipped with AEBS.

Consequences of each case were assessed based on the following principles:

- If the car velocity at the moment of impact is higher than 0 km/h, an event occurs,
- If the car velocity at the moment of impact is higher than 20 km/h, an accident occurs,
- The relationship between the probability of a pedestrian death or severe injury and impact velocity is based on statistical studies [1], [6], [8].

In the analysis the following designations are used:

t – time,

t_R – response (reaction) time

- Without AEBS:

$$t_{R\ wihout\ AEBS} = t_{R\_driver} + t_{DB} + 0.5t_{BDI}, \tag{1}$$

$t_{R\ driver}$ – driver's reaction time,

t_{DB} – delay in brake activation,

t_{BDI} – time of braking deceleration increase;

- With AEBS:

$$t_{R\ with\ AEBS} = t_{R\_AEBS} + t_{DB}, \tag{2}$$

$t_{R\ AEBS}$ – AEBS reaction time,

t_{DB} – delay in brake activation;

t_S – time to stop the vehicle,

s – distance from the pedestrian,

s_R – distance during response time,

s_B – distance during braking,

s_S – distance to stop the vehicle,

a – braking deceleration,

V – velocity ,

V_0 – car initial velocity,

T_{TC} – time to collision (risk time)

$$TTC = \frac{s}{V_0}, \tag{3}$$

age – pedestrian age.

In addition, the following physical relationships were applied:

1) $If\ t \le t_R\ and\ s \le s_R\ (uniform\ motion)\ then:$

$$s(t) = V_0 \cdot t, \tag{4}$$

$$V(t) = V_0. \tag{5}$$

2) $If\ t_R < t < t_S\ and\ s_R \le s \le s_S\ (uniformly\ decelerated\ motion)\ then:$

$$s(t) = s_R + s_B(t), \tag{6}$$

$$s_R = V_0 \cdot t_R\ , \tag{7}$$

$$s_B(t) = V_0 \cdot (t - t_R) - 0.5a(t - t_R)^2\ , \tag{8}$$

$$V(t) = V_0 - a(t - t_R). \tag{9}$$

Substituting $t' = t - t_R$ and making transformations the following formula can be obtained:

$$V = \sqrt{V_0^2 - 2as_H} \tag{10}$$

3) $If\ t \ge t_Z\ and\ s \ge s_S\ (car\ stopped\ before\ a\ potential\ collision)\ then:$

$$V(t) = 0. \tag{11}$$

3. The input data to the Monte Carlo analysis

In the Monte Carlo analysis, based on literature data [2], [3], [4], [9] the following average values and distributions were assumed (Table 1).

Table 1. Data for Monte Carlo Analysis

variable	$t_{R\,driver}$[1] driver's reaction time	t_{DB} delay in brake activation	$0.5t_{BDI}$ 0.5 time of braking decele-ration increase	$t_{R\,AEBS}$[2] AEBS reaction time	a braking decele-ration	V_0 car initial velocity	*age* pedestrian age
Average	in fig.1 $(\tilde{t}^* = 0)$	0.15 s	0.17 s	0.20 s	$8\,\frac{m}{s^2}$	$55\,\frac{km}{h}$	45 years
Type of distribution	normal for $\tilde{t}$	normal	normal	constant	normal	log-normal	own[3]
Standard deviation	0.1 for $\tilde{t}$	0.05	0.02	----	0.667	0.25	----

1. $t_{R_{driver}} = t_{R_{driver}}{}^*(TTC) + \tilde{t};\quad (\tilde{t}^* = 0)$, when $\tilde{t}$ is a pseudo random number with the distribution adopted in Monte Carlo method.
The average values marked *.

2. It was assumed that the camera, which operates at a frequency of 50 Hz, should analyze few samples of image and process information in order to recognize a pedestrian. In addition, radar operating at a frequency of 200 Hz has to recognize the movement of pedestrian.

3. This is combination of two normal distributions selected in such a way that the results approximated the age pyramid Polish society over 15 years in 2016 [9] (Fig. 2f).

Using the results of the tests on the driving simulator [4], the average the driver's reaction time was dependent on the predicted time to collision – TTC (fig. 1).

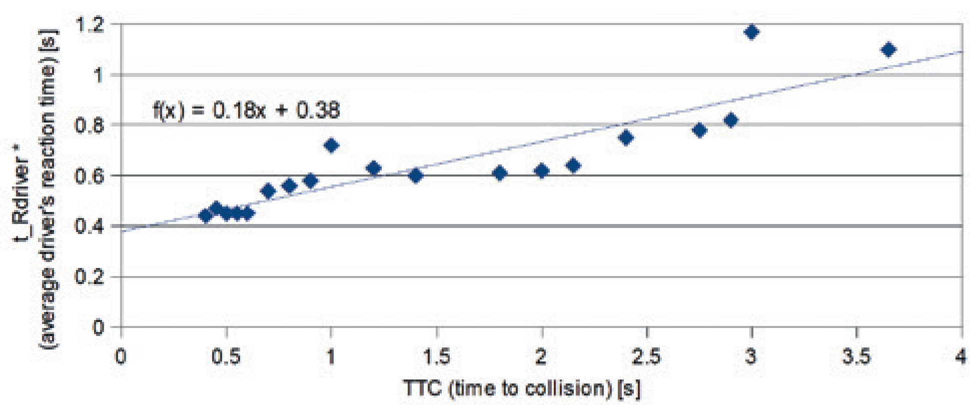

Fig. 1. The relationship between time to collision and driver's reaction time in a simulator [4]

In Figure 1, it can be seen that the average driver's reaction time is linearly TTC-dependent, which allows determining the following relationship:

$$t_{R_{driver}} = 0.18\,TTC + 0.38\, + \tilde{t}\,. \tag{12}$$

The driver's reaction time could be underrated because the observations were made in a simulator. For this reason an improved relationship was used in Monte Carlo method:

$$t_{R_{driver}} = 0.18\,TTC + 0.48\, + \tilde{t}\,. \tag{13}$$

The distributions of used variables (probability density functions), described in Table 1, are shown in Fig. 2.

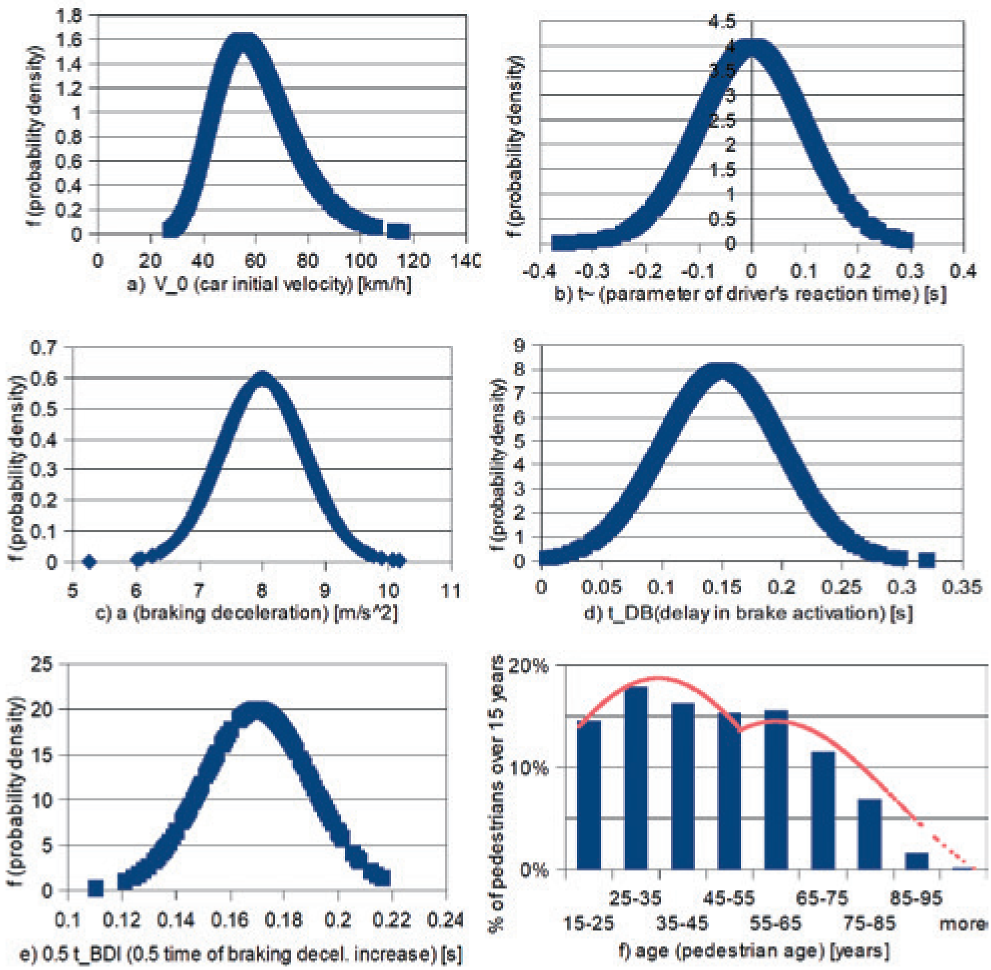

Fig. 2. Probability density functions for selected parameters

It should be noted that the distributions might vary depending on the particular simulation. Because age distribution (Fig. 2f) is a combination of two normal ones, in this case percent of pedestrians in different age groups was also shown.

4. The probability of a pedestrian fatality or severe injury

Based on many different studies [1], [6], [8] the probabilities of a pedestrian death and serious injuries as a function of impact velocity were determined (Table 2).

Table 2. Probability of severe injury and fatality as a function of impact velocity. Statistical data [1], [6], [8]

Study	Data	other		Z_{si} (Probability of severe injury* [%])					Z_f (Probability of fatality [%])				
				10	25	50	75	90	10	25	50	75	90
				impact speed [km/h]					impact speed [km/h]				
Ashton & Mackay (1979)	UK, 1970s, Richards (2010) calculations								48	58	64	74	79
Davis (2001)	UK, 1966-1969& 1973-1979								53	61	69	79	87
Rosen & Sander (2009)	Germany, 1999-2007, pedestrians 15+years struck by front of car	none adjusted							51	64	77	88	101
		adjusted for age 45							53	66	77	88	101
Richards (2010)	UK, 2000-2009, pedestrians struck by front of car								53	61	72	82	100
Tefft (2011)	US, 1994-1998, pedestrians 15+years, struck by forward-moving car or light truck	none adjusted	cars						45	58	71	84	97
		age, height, weight, BMI, vehicle type adjusted	cars						48	61	74	85	98
			cars and light trucks	25	37	49	62	74	37	51	68	80	93

* AIS 4 or greater and it includes death irrespective of AIS score

Using data from Table 2, the relationships between probabilities and impact velocity can be determined:

- for death of pedestrian it is: $$Z_f(v) = \frac{100}{1+e^{6.6-0.0915v}} \quad , \tag{14}$$
- for severity injury it is: $$(v) = \frac{100}{1+e^{4.505-0.0917v}} \ . \tag{15}$$

The form of these equations ($Z(v) = \frac{100}{1+e^{x_1-vx_2}}$) is taken from literature [6]. The results are shown in graphs (Fig. 3 and Fig. 4).

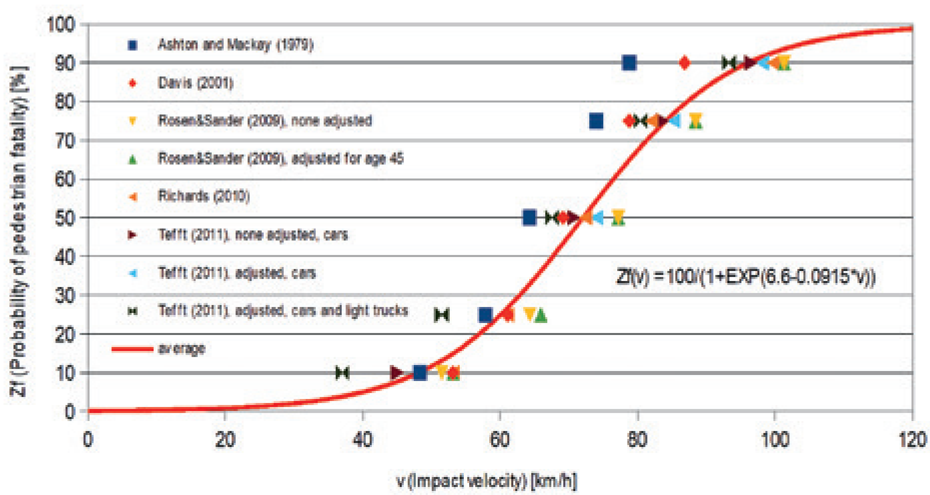

Fig. 3. Probability of death as a function of impact velocity

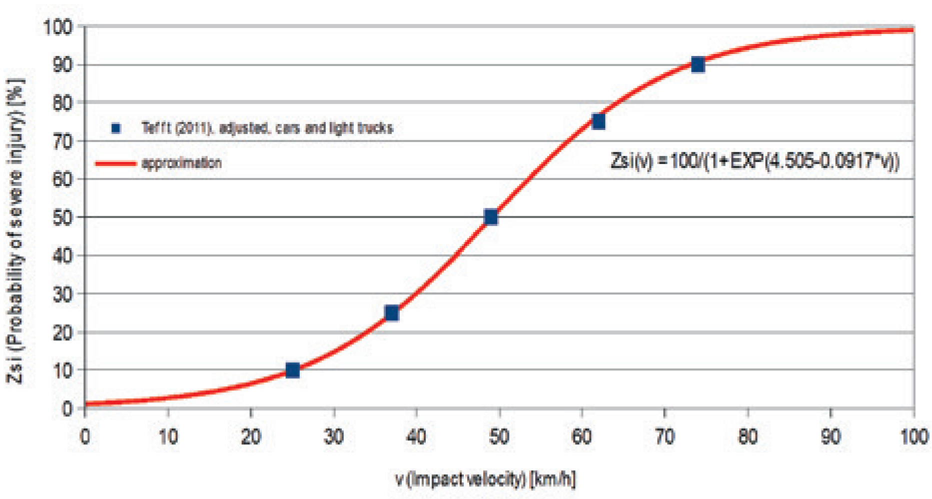

Fig. 4. Probability of severe injury as a function of impact velocity

Based on Tefft's study (Figure 2 in [8]) it is possible to determine the relationship between Z and pedestrian age. The offset of graph on the x-axis is approx. 0.4 km/h for 1 year. Assuming that formulas (14) and (15) refer to 45-year-pedestrian, $Z(\mathrm{v}$, age) can be determined:

- for death of pedestrian it is: $$Z_f(v, age) = \frac{100}{1+e^{6.6-0.0915(v+0.4(age-45))}}, \quad (16)$$
- for severity injury it is: $$Z_{si}(v, age) = \frac{100}{1+e^{4.505-0.0917(v+0.4(age-45))}}. \quad (17)$$

This formulas (16) and (17) are correct for 15-year-pedestrians and older.

The probabilities Z_f and Z_{si} for pedestrians of different ages (25, 45 and 75 years) were shown in Fig 5.

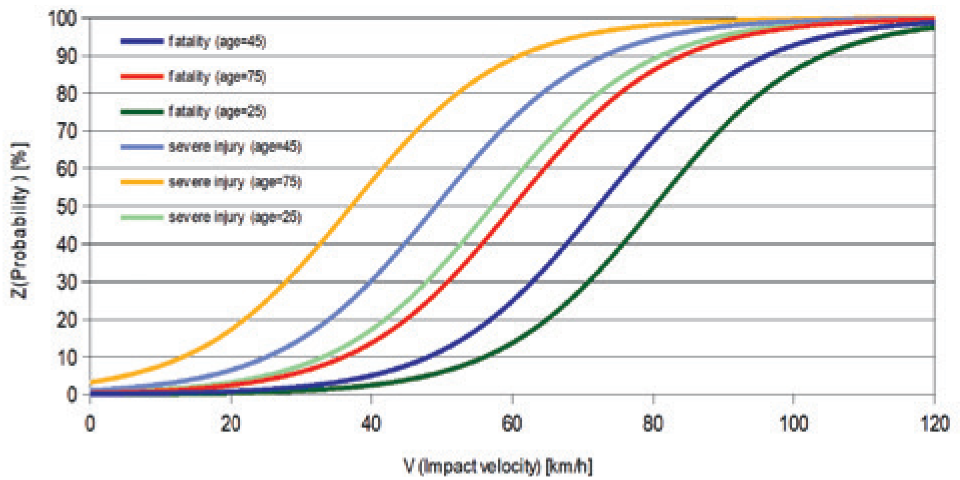

Fig. 5. Probabilities as a function of impact velocity and pedestrian age

5. Results of the analysis using the Monte Carlo method

Risk analysis for situation: hitting a pedestrian was performed for 10 different distances (5, 10, 15, 20, …, 50 m). Values of cumulative distribution function were randomized 1,000 times for each distance between pedestrian and car for the following parameters:

- car's initial velocity,
- driver's reaction time,
- braking deceleration,
- delay in brake activation,
- time of braking deceleration increase,
- pedestrian's age.

Normal and log-normal distributions were applied, except pedestrian's age which was presented as a special distribution approximating the population pyramid in Poland (Figure 2f).

The impact velocity for car without and with AEBS was calculated. Knowing the impact velocity and pedestrian age, number of undesirable events (V>0 km/h) or accident (V>20 km/h) and probability of fatality or severe injury could be determined for each distance. To calculate these probabilities cases when an undesirable event for car not equipped with AEBS occurred were taken into account. In order to estimate the values for all distances the weighted average should be determined. The weights for each distance were numbers of events for car without AEBS.

Formulas for each distance are as follows:

$$Z_{f\ (without\ \ AEBS)} = \frac{\sum_{n=1}^{1000} Z_{f,n\ (without\ AEBS)}}{NE_{(without\ AEBS)}}, \tag{18}$$

$$Z_{f\ (with\ \ AEBS)} = \frac{\sum_{n=1}^{1000} Z_{f,n\ (with\ \ AEBS)}}{NE_{(without\ AEBS)}}, \tag{19}$$

$$Z_{si\ (without\ \ AEBS)} = \frac{\sum_{n=1}^{1000} Z_{si,n\ (without\ AEBS)}}{NE_{(without\ AEBS)}}, \tag{20}$$

$$Z_{si\ (with\ \ AEBS)} = \frac{\sum_{n=1}^{1000} Z_{si,n\ (with\ AEBS)}}{NE_{(without\ AEBS)}}, \tag{21}$$

$$Reduction\ NE = \frac{NE_{(with\ AEBS)} - NE_{(without\ AEBS)}}{NE_{(without\ AEBS)}}, \tag{22}$$

$$Reduction\ NA = \frac{NA_{(with\ AEBS)} - NA_{(without\ AEBS)}}{NA_{(without\ AEBS)}}, \tag{23}$$

$$Reduction\ Z_f = \frac{Z_{f\ (with\ AEBS)} - Z_{f\ (without\ AEBS)}}{Z_{f\ (without\ AEBS)}}, \tag{24}$$

$$Reduction\ Z_{si} = \frac{Z_{si\ (with\ AEBS)} - Z_{si\ (without\ AEBS)}}{Z_{si\ (without\ AEBS)}}. \tag{25}$$

Used symbols:

Z_f – probability of pedestrian death (fatality),

Z_{si} – probability of pedestrian severe injury,

n – number of simulation in Monte Carlo Method,

N_E – number of (undesirable) events,

N_A – number of accidents.

Formulas for all situations is as follows:

$$NE_{all} = \sum_{i=1}^{10} NE_i\ , \tag{26}$$

where i is $\frac{1}{5}\cdot$distance between pedestrian and car.

$$NA_{all} = \sum_{i=1}^{10} NA_i\ , \tag{27}$$

$$Z_{all} = \frac{\sum_{d=1}^{10}(Z\ d \cdot NE_{(without\ AEBS)_i})}{\sum_{d=1}^{10} NE_{(without\ AEBS)_i}}, \tag{28}$$

$where\ Z\ can\ be\ Z_f\ or\ Z_{si}\ (with\ or\ without\ AEBS)$.

$$Reduction\ NE_{all} = \frac{NE_{(with\ AEBS)all} - NE_{(without\ AEBS)all}}{NE_{(without\ AEBS)all}}, \quad (29)$$

$$Reduction\ NA_{all} = \frac{NA_{(with\ AEBS)all} - NA_{(without\ AEBS)all}}{NA_{(without\ AEBS)all}}, \quad (30)$$

$$Reduction\ Z_{f\ all} = \frac{Z_{f\ (with\ AEBS)all} - Z_{f\ (without\ AEBS)all}}{Z_{f\ (without\ AEBS)all}}, \quad (31)$$

$$Reduction\ Z_{si\ all} = \frac{Z_{si\ (with\ AEBS)all} - Z_{si\ (without\ AEBS)all}}{Z_{si\ (without\ AEBS)all}}. \quad (32)$$

The results of the analysis using the above formulas are shown in Table 3 and Fig. 6.

Table 3. The influence of the application of AEBS on the reduction of analyzed parameters for different distances between pedestrian and car

distance s [m]	without AEBS				with AEBS				reduction				weight
	number of:		probability		number of:		probability		number of:		probability		
	events	accidents	Z_f [%]	Z_{si} [%]	events	accidents	Z_f [%]	Z_{si} [%]	events	accidents	Z_f [%]	Z_{si} [%]	
5	1000	1000	27.03	62.99	999	992	26.44	61.31	0.10%	0.80%	2.21%	2.67%	1000
10	998	995	26.98	62.70	945	898	18.78	46.13	5.31%	9.75%	30.41%	26.43%	998
15	981	946	25.68	58.80	768	661	11.79	30.74	21.71%	30.13%	54.08%	47.71%	981
20	909	854	22.53	51.57	492	415	7.57	20.48	45.87%	51.41%	66.39%	60.29%	909
25	769	693	19.64	45.68	306	258	5.21	14.53	60.21%	62.77%	73.46%	68.18%	769
30	589	519	18.09	42.98	196	166	3.93	11.21	66.72%	68.02%	78.29%	73.92%	589
35	428	365	17.23	41.97	116	94	3.09	8.63	72.90%	74.25%	82.05%	79.43%	428
40	308	268	16.32	41.07	65	51	2.48	6.74	78.90%	80.97%	84.84%	83.58%	308
45	219	193	15.43	40.34	34	28	1.97	5.59	84.47%	85.49%	87.20%	86.15%	219
50	163	134	16.32	36.80	18	17	1.41	4.60	88.96%	87.31%	91.37%	87.50%	163
all situations	6364	5967	22.60	52.80	3939	3580	11.42	28.54	38.10%	40.00%	49.46%	45.94%	

Based on the data in Table 3 and Figure 6, it can be concluded that the reduction of probability of accident and injury (severe or fatal) increases with the distance between the car and pedestrian. This is because for small distances not only man but also AEBS may not be able to react in a timely manner (especially for high velocity). For large distances quick action of the automatic braking system significantly reduces the risk of pedestrian.

For all situations the probability of undesirable event and the accident are reduced by approximately 40 percent, whereas the probability of loss of life or serious injury by nearly half. The results are similar to studies carried out by the German Insures Accident Research [5]. In that case, the safety potential (reduction accidents) was analysed for a similar system, ie. Collision Mitigation Braking System 3rd generation (CMBS 3). This coefficient was 40.8%, which is very close result. It should be noted that analysis concerned not only about situations related to the pedestrian but all cases of accidents and was made with the use of some other method.

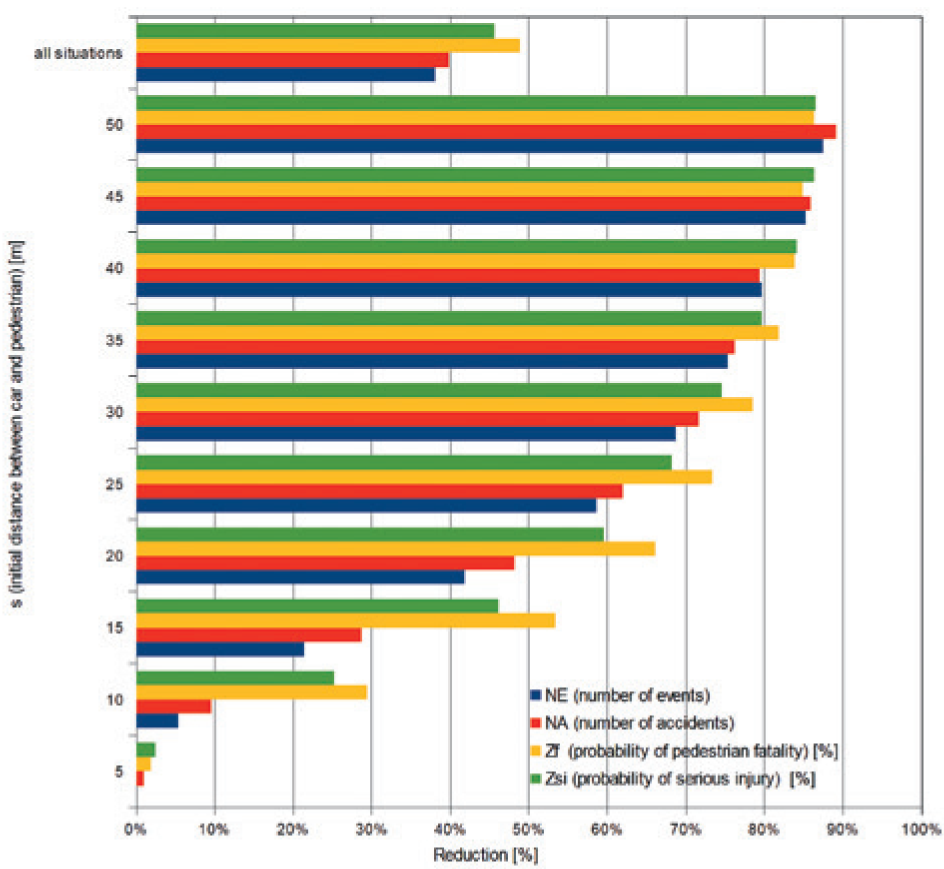

Fig. 6. The influence of the application of AEBS on the reduction of analyzed parameters for different distances between pedestrian and car

6. Conclusions

The effectiveness of driver assistance systems on the example of the AEBS was demonstrated with the use of quite simple model. The applied method shows how to estimate the benefits of introducing such systems without data relating to crashes of cars equipped with AEBS (this data is missing or inaccurate). All calculations are based on general statistics, typical distributions of parameters and simple physical dependencies. The results are valuable because of the possibility to estimate the benefits of these systems that are not yet widespread and will be introduced in the near future.

Application AEBS will have a significant influence on the pedestrian safety. The number of accidents with pedestrians can be reduced up to 40% and the probability of injuries (serious or fatal) by half. These coefficients are dependent on the distance between car and pedestrian. The reduction of probability of accident or injuries increases with increase of the distance.

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The full text of the article is available in Polish online on the website
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References

[1] Ashton S J, Mackay G M. Some Characteristics of the Population who Suffer Trauma as Pedestrian when Hit by Cars and Some Resulting Implications, Accident Research Unit, Departament of Transportation and Environmental Planning, University of Birmingham, 1979.

[2] Bułka D, Walczak S, Wolak S. Proces hamowania–aspekt prawny i techniczny w ujęciu symulacyjnym i analitycznym, Conference materials of III Conference „Rozwój techniki samochodowej a ubezpieczenia komunikacyjne", WSB, 2006, Radom.

[3] Gaca S, Jamróz K, Ząbczyk K. Analiza wybranych aspektów zachowania użytkowników dróg. Raport Końcowy. Podsumowanie Badań prędkości. Na zlecenie KRBRD, 2004.

[4] Guzek M, Jurecki R, Lozia Z, Karendał M, Zdanowicz P. Badania reakcji kierowców na pieszego wychodzącego z prawej strony, realizowane w symulatorze jazdy samochodem, Autobusy. Technika, Eksploatacja, Systemy Transportowe, 2010: 6.

[5] Kuehn M, Hummel T, Bende J. Benefit Estimation of Advanced Driver Assistance Systems for Cars Derived from Real-life Accidents, German Insurers Accident Research, 21st International Technical Conference on the Enhanced Safety of Vehicles ESV 2009, Stuttgart.

[6] Richards D C. Relationship between Speed and Risk of Fatal Injury: Pedestrians and Car Occupants, Road Safety Web Publications No. 16, Department for Transport, 2010, London.

[7] Szopa T. Niezawodność i bezpieczeństwo, Oficyna Wydawnicza PW, Warszawa 2009.

[8] Tefft B.C: Impact Speed and a Pedestrian's Risk of Severe Injury or Death, AAA Foundation for Traffic Safety, Washington, 2011.

[9] www.populationpyramid.net/pl/polska/2016, access date: 02.11.2016.