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ROAD USERS' BEHAVIOUR STUDY IN AREAS OF ZEBRA CROSSWALKS

Summary. Pedestrian safety on crosswalks is extremely vital in Poland since 2015, when the first study on road users' behaviour on driver–pedestrian encounters in areas of zebra crosswalks were conducted. The second study was carried out in 2018 and its results are published in this article for the first time. The results of the project helped lead to changes in pedestrians' safety regulations in Poland, increasing the safety of pedestrians in areas of crossing. Since June, the 1st, 2021, drivers of oncoming cars approaching a zebra crossing are obliged to stop to allow pedestrians approaching from the sidewalk to cross the zebra crossing. Data to assess pedestrian safety presented in this article combine a new approach that is a combination of different diagnostic techniques: a surrogate safety measure (non-accident-based indicators) and the traditional approach: statistical analysis. As a result of the study, the most frequent categories of interactions between drivers and pedestrians and pedestrians itself were characterized on crossing facilities. Videos recording pedestrians' and drivers' behaviours, and vehicle speed measurements at pedestrian crossings from 2018 allow to assess the safety of 7 000 pedestrians during behaviour observation in on-site fields: on all crossing facilities, except with light signalization, 55% of pedestrians had to stop and wait at the sidewalks to cross, before an oncoming car. Only 45% of drivers approaching not signalised zebra crossings gave way to pedestrians. Pedestrians aged 60+ entering the road on marked crossings without traffic light waited longer to cross than younger. In residential areas with high traffic volume more drivers stopped at non signalised crossings and gave way to pedestrians. At low speed of vehicle in urban areas pedestrians felt safer and were ready to enter the crossing; their behaviour was more predictable. Results showed dangerous pedestrian behaviours on signal-regulated crossing facilities who failed to obey the traffic lights (7% of red-light crossings). 8% of observed pedestrians crossed the street outside designated pedestrian crossings. Video-recorded speed measurements of over 32 000 vehicles on-site study fields of pedestrian crossings showed that the speed of vehicles was higher than permitted. This article presents the newest characteristics of traffic and pedestrian' behavior at crossings together with measurements of pedestrians' speed and loss of pedestrians' time on different road cross sections in Poland in 2018.

1. PEDESTRIANS' RISKS ON POLISH ROADS

Unprotected by a car's body against the speed and mass of a crash, pedestrians are vulnerable road users (VRUs) who are at risk in all countries. As 15-25% of all journeys are undertaken on foot, road infrastructure and designated zebra crossing should prioritize safe crossing of pedestrians. Statistics show that the risk to pedestrians is one of the main problems identified in traffic safety strategies at the global level as well as in individual countries. It is therefore particularly important to create a transport system that guarantees the safety and meets the needs of both drivers and pedestrians. Today's concept of self-explaining and forgiving road infrastructure (more intuitive and natural for road users)

result road design to prevent and correct errors made by humans. In this context, the problem of pedestrian safety as vulnerable road users deserves special attention.

Meanwhile, the risk to pedestrian safety in Poland is particularly high and has remained so for years. A comparison of data on road accidents in the European Union (UE) indicates that the risk to pedestrians on Polish roads is very high, one of the highest in EU (Fig.1). The risk rate is 21 pedestrain deaths per million population, which is two times higher than the average in EU countries and 7 times higher than that in Holland or Sweden, which have the lowest fatality rates. The proportion of fatalities among female pedestrians is much higher than male pedestrians. Seniors and children are age groups which walking is particular popular. Half of all pedestrians in Europe die aged 65 years or older.

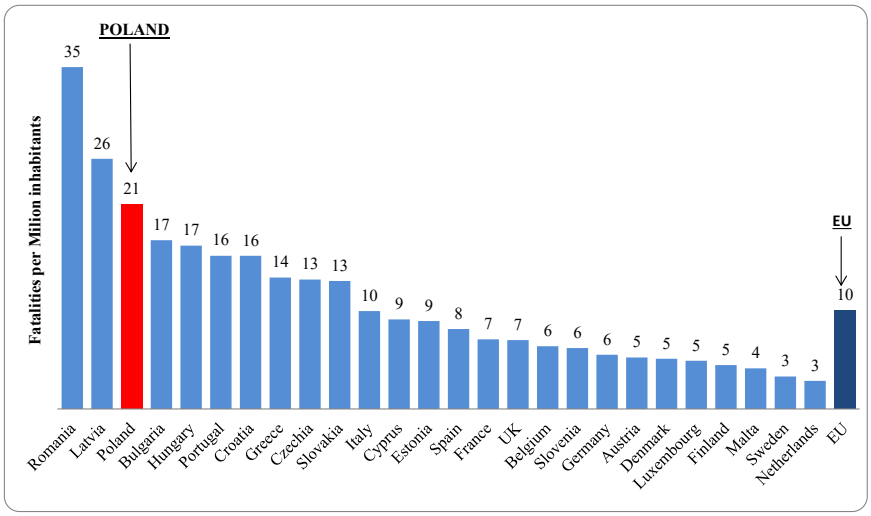

Fig. 1. Pedestrian fatality rates per million population by EU country, 2018 [1]

Marked pedestrian crossing facilities, their location, type and design have an impact on pedestrian' safety. Pedestrian crossings can be located in urban or nonurban areas and on junctions or outside junctions with or without traffic light signalization. Design of road infrastructure with number of lines on carriageway is very important either. There could be different type of road cross section depending on number of carriageways and their lanes: 1x2 (single carriageway with two lanes), 1x4 (single carriageway with four lanes), 2x2 (dual carriageway with two lanes each direction), 2x4 (dual carriageway with four lanes each direction). All these elements, together with traffic control measures, should minimize the risk of accidents and make urban road infrastructure safer for pedestrians.

Measures that can improve the safety of marked crossroads are elevated walkways (or speedbumps), centre island (refuge) in the middle of the road, shorter stretches to crossing; extension of sidewalks (to reduce the distance that pedestrians have to travel, prevent parking of cars/ improve visibility conditions) and illumination of pedestrian crossings to draw attention. Slower driving speeds or physically separating transport modes are most effective for the safety and comfort of pedestrians on crossing facilities.

Factors identified as contributing to pedestrian' accidents are road environment; lack of or poor design of crossing facilities; high speed of motorized vehicles; lack of pedestrian visibility due to not wearing reflective materials at night, risky behaviours of all road users [2].

Marked pedestrian crossings (zebra paths) with non-signaled crossing facilities located on single carriageways with no more than two lanes shows relatively low crash risk. Risk increases on marked crossings on busy dual carriageways with more than two lanes. Signal-regulated crossing facilities generate two major problems, which are pedestrians who fail to follow the traffic lights and conflicting traffic light phases for turning vehicles and pedestrians at their exit approach [2].

There were 793 killed pedestrians (27% of all road fatalities) and 2 474 seriously injured (which was 23% of all road seriously injured) in Poland in 2019 (Tab.1). In urban (builtup) areas, 17% of all road

accident casualties involved pedestrians. Pedestrians who were hit by cars at crosswalks in builtup areas made up 7% of all road deaths (Fig.2) and 9% of all road injuries in Poland in 2019 (Fig. 3).

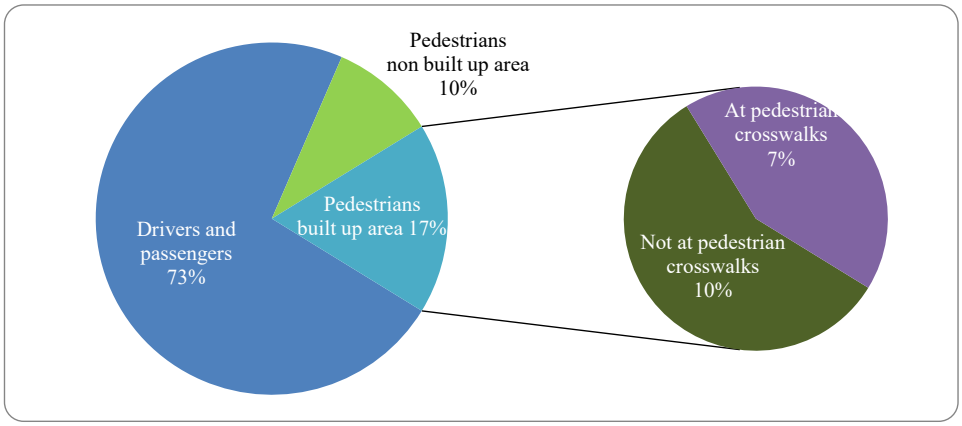

Fig. 2. Pedestrian fatalities in Poland in 2019 [3]

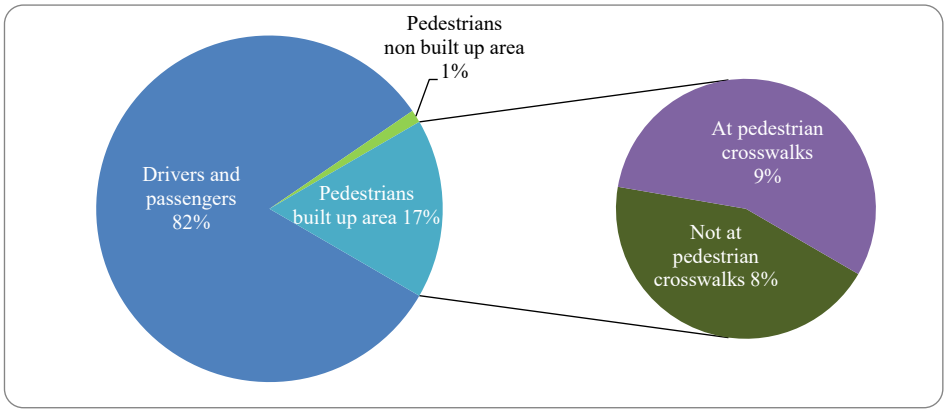

Fig. 3 Pedestrian injuries in Poland in 2019 [3]

Statistical data presented below show the risk to pedestrians on Polish roads while crossing different types of crossings according to the type of section of the road (on or outside an intersection) and traffic light signalization (with or without) [Tab. 1]. Data showed pedestrians to be at the highest risk of accidents, death and serious injuries in Poland on marked crossing facilities not located at junctions without traffic lights (7% of all accidents, 5% of all fatalities and 7% of all seriously injured). The lowest risk of accidents with fatalities among pedestrians was on crosswalks located outside an intersection, but with traffic lights (0, 4% of all accidents, 0, 1% of all fatalities and 0, 5% of seriously injured). Crossing the street is very risky at a non-signalized type of section outside a junction, where there are plenty of driver–pedestrian conflicts points. This kind of crossing facility increases the risk of accidents, which is higher with more road lines on a carriageway. Zebra paths located on non-signalized intersections are more risky for pedestrians than intersections with traffic lights. Statistics in Tab. 1 indicate that crossing facilities with traffic lights provided more safety and comfort to pedestrians [3]. One of the most types of pedestrian' accident at zebra crossing is at non-signalised intersection. This pedestrians' crash scenario is when the vehicle is turning right and pedestrian is entering the crossing, where usually drivers are focus on traffic coming from left.

Pedestrian crossing is that part of the road where pedestrian safety is a priority. This can be achieved through appropriate actions such as legal regulations, infrastructure design, education and enforcement. However, for actions to be effective, they must be based on road accident analyses using road safety diagnostic techniques, i.e., analysis of road accidents, naturalistic behavioral observations and on-site interactions between pedestrians and drivers. Observation on road users' behaviour: video-based traffic

pedestrians and drivers encounters recorded on-site study fields belong to indicators of non-accident road safety diagnostic techniques [4].

Table 1

Number of accidents, fatalities and serious injuries among pedestrians on pedestrian crosswalks in Poland in 2010 and between 2017 and 2018 [3]

Year	Accidents		Fatalities		Serious injuries	
	No.	%*	No.	%*	No.	%*
Accidents with fatalities among pedestrians in general						
2010	11285	29%	1236	32%	3246	28%
2017	8107	25%	873	31%	2825	25%
2018	7428	23%	803	28%	2655	24%
2019	6887	23%	793	27%	2474	23%
2019/2018	-7%		-1%		-7%	
Accidents with fatalities among pedestrians on crosswalks in general						
2010	3308	9%	191	5%	1022	9%
2017	4072	12%	259	9%	1466	13%
2018	3713	12%	271	9%	1367	12%
2019	3449	11%	234	8%	1312	12%
2019/2018	-7%		-14%		-4%	
Accidents with fatalities among pedestrians on crosswalks, on junctions without traffic lights						
2010	1001	3%	55	1%	293	3%
2017	1144	3%	51	2%	439	4%
2018	976	3%	67	2%	359	3%
2019	882	3%	58	2%	307	3%
2019/2018	-10%		-13%		-14%	
Accidents with fatalities among pedestrians on crosswalks, on junctions with traffic lights						
2010	476	1%	21	1%	129	1%
2017	538	2%	24	1%	186	2%
2018	474	1%	22	1%	160	1%
2019	399	1%	19	1%	156	1%
2019/2018	-16%		-14%		-3%	
Accidents with fatalities among pedestrians on crosswalks, outside junctions, no traffic lights						
2010	1664	4%	98	3%	541	5%
2017	2195	7%	170	6%	769	7%
2018	2083	7%	170	6%	775	7%
2019	2051	7%	155	5%	796	7%
2019/2018	-2%		-9%		3%	
Accidents with fatalities among pedestrians on crosswalks, outside junctions, with traffic lights						
2010	167	0,4%	17	0,4%	59	1%
2017	195	1%	14	0,5%	72	1%
2018	180	1%	12	0,4%	73	1%
2019	117	0,4%	2	0,1%	53	0,5%
2019/2018	-35%		-83%		-27%	
Hitting a pedestrian/other passenger areas (crosswalks, bus stop)						
2010	493	1%	23	1%	142	1%
2017	424	1%	21	1%	157	1%
2018	437	1%	13	0,5%	152	1%
2019	403	1%	12	0,4%	141	1%
2019/2018	-8%		-0,1		-7%	

* % all traffic accidents, fatalities and serious injuries in each year

Studies on the risks at pedestrian crossings are carried out by independent experts from various countries. Some studies focus on detailed analyses of road accidents in terms of their location of occurrence, characteristics of the perpetrators and victims and the circumstances of their occurrence.

These are factors that have a direct impact on the occurrence of incidents [5, 6]. Another part of the research involves road users' direct behavioral observations. The impact of indicators such as pedestrian's age and gender, time of day, vehicle speed and traffic intensity on decisions to cross a road is examined [7, 8]. Research is carried out using naturalistic observation techniques [7, 9, 10] as well as using simulators [10].

Models of pedestrian' behavior and models of pedestrian– driver interactions are developed based on observation studies. It enables the development of ready-to-use software to collect data for further analysis [9, 7]. Behavioral models simulating pedestrians– driver encounters are developed as well [1]. Use of models of behavioral observations enabled the identification of new solutions aimed at improving pedestrian safety such as special horizontal or vertical marking, signaling indicating approach or the presence of a pedestrian at zebra crosswalks [1, 9, 13]. Determining the risk of road traffic during on-site real observations is a labor-intensive and time-consuming research method.

The Secretariat of the National Road Safety Council commissioned an observation study on interactions between pedestrians and drivers at an area of zebra crossings in Poland in 2018 [12]. The objective of the research was to provide data about naturalistic pedestrian behavior and pedestrian–driver interactions in zebra paths to formulate countermeasures to improve pedestrian safety on Polish roads.

According to the adopted methodology video-based behavioural data were collected. This method was the most effective tool used for safety analysis at pedestrian crossings. It enabled data collection for analysis due to the specific characteristics of behaviors of a statistically representative group of road users in various road traffic and weather conditions. It also allowed analysis of behaviors of road users in terms of age, gender.

2. METHODOLOGY

The aim of the research on pedestrians' and drivers' realistic behaviors was to analyze their encounters in areas of pedestrian crossings to improve road safety.

It was agreed that on-site study locations (real-life observation fields) from 4 voivodships will provide sufficient research data to assess the whole country. Based on the analysis of road safety and pedestrian accidents in Poland, in 2017, voivodships were selected for this study.

Data were analyzed for individual voivodships according to:

- road safety rates,
- comparison of safety rates over the past few years,
- number of accidents with pedestrians and
- proportion of pedestrian accidents of the total number of accidents in the voivodship.

Four voivodships of Poland, Lodz, Silesia, Mazovia and Greater Poland, were selected to carry out the research. In these voivodships, the proportion of pedestrian' accidents were relatively the highest.

The total number of accidents involving pedestrians in these 4 voivodships accounted for 45% of all accidents of this type in Poland. Pedestrian deaths in these accidents accounted for 50% of all fatalities. The Mazovia voivodship was characterized by the highest rate of risk to inhabitants (12 fatalities per 100,000 inhabitants) in the country, in voivodships of Greater Poland and Lodz, the rates were at the average level (8,2 – 8,8 fatalities per 100,000 inhabitants) and the Silesian voivodship had the lowest rate of fatalities in the country (5,4 fatalities per 100,000 inhabitants).

This study was performed in real- life field conditions (on-site) in 80 locations of Poland in 2018. The criteria of selection of real-life observation areas were the same in each voivodship. Road sections with permitted speed limits of 50 km/ h and 70 km /h both in built-up and non-built-up areas in large cities and small towns were examined. Locations of pedestrian crossings were examined outside intersections and at intersections with and without traffic lights.

One of the most important criteria for proper selection of on-site study locations was lack of physical restrictions. Road section design and the surroundings near the crosswalk location should not have physical restrictions in visibility, as these would not allow free speed movement of vehicles on carriageway (no road-, slope grades).

On-site observations of pedestrians' and drivers' behaviours were then supplemented with questionnaire (opinion) studies. Depending on the nature and scope of the study, appropriate measurement methods and tools were used.

2.1. On-site observation fields study

An on-site observation study was carried out using the picture recording method, followed by coding and processing of the recorded video material to analyze pedestrian behavior and pedestrian–driver interactions. Recording of driver–pedestrian encounters was carried out using 2 high-resolution video cameras (minimum recording resolution of 1280 x 720 pixels at 25 frames/s) placed on masts of variable height from 3 meter high. Camera installation and range of the recorded pictures are shown below (Fig. 4, 5).

Movement of pedestrians and vehicles was recorded while:

- an oncoming vehicle was approaching a pedestrian crossing in front of zebra at a distance of at least 100 meters,
- a pedestrian was approaching the zebra crossing (walking on the sidewalk) at a distance of at least 5 meters before the crosswalk,
- at the zebra crosswalk and
- a vehicle was leaving the pedestrian crossing, behind the zebra crossing at a distance of at least 10 meters.

Fig. 4. Camera installation method - side view [12]

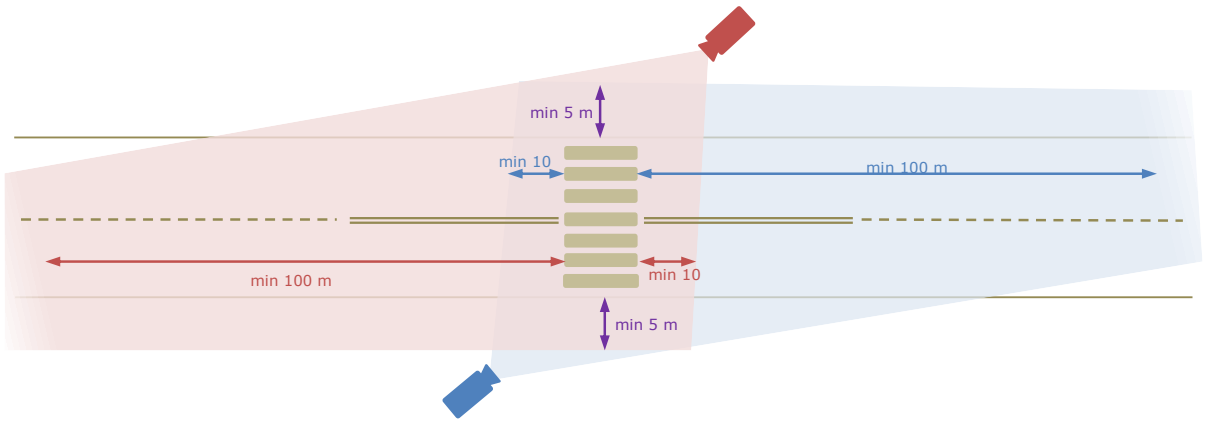

Fig. 5. Camera installation method - top view [12]

The measurement technique used in this research was video recording using a set of cameras for further laboratory analysis. Videos were recorded on weekdays and weekends, except holidays, during the day (one hour after sunrise and one hour after sunset). The recordings were performed at designated pedestrian crossings at intersections and outside intersections in large cities, small towns and outside built-up areas.

The recorded video material was analyzed to calculate the speed of pedestrians and vehicles in areas of pedestrian crossing, behaviour of pedestrians and pedestrian–driver encounters.

Vehicle speed was tested at 10-meter intervals. Only free speed of vehicles was measured i.e., drivers could choose their speed. Criteria of vehicles' free movement were time interval between each other

vehicles; time' gap was 6 s outside built-up area and 5 s in built-up area. Speed measurement of pedestrian, first from the group was recorded and analyzed.

Pedestrian–driver encounters at zebra crosswalks were classified into the following categories:

- no pedestrian,
- pedestrian approaching the crossing,
- pedestrian waiting before the crossing (on a sidewalk),
- pedestrian entering the crossing (i.e. pedestrian enters crossing with one foot),
- pedestrian who is at the zebra crossing (i.e. pedestrian who fully entered the crossing),

The following drivers' behaviours toward pedestrians in the crossing area were analyzed:

- driver gives way (the vehicle stops before the crossing or clearly slows down) to the pedestrian who is on the sidewalk approaching the crossing,
- driver gives way (the vehicle stops before the crossing or clearly slows down) to the pedestrian who is waiting on the sidewalk, before entering the zebra crossing,
- driver gives way (the vehicle stops before the crossing or clearly slows down) to the pedestrian who is entering the road,
- driver gives way (the vehicle stops before the crossing or clearly slows down) to the pedestrian who is at the crossing,
- driver fails to stop and puts pressure on pedestrian who fully entered the crossing,
- driver brakes sharply in front of the pedestrian crossing.

The hazardous pedestrian behaviors identified and classified at the area of crossing were as follows:

- pedestrian crosses the road in nonpermitted locations near designated zebra crosswalks (up 100 m),
- pedestrian enters the road unexpectedly,
- pedestrian walks while the red-light sign is on (crosswalks with pedestrian-activating systems),
- pedestrian talks on the mobile phone,
- pedestrian writes Text messages/ uses the touch screen of electronic devices,
- pedestrian stands before the crossing, gives way to vehicles and
- pedestrian listens to the music (headphones on ears).

The objective of the survey was to determine drivers' and pedestrians' knowledge of and opinions about their attitudes at pedestrian crossings. Surveys were complemented with realistic video recordings performed during on-site study fields at crosswalk locations.

3. PEDESTRIANS AND DRIVERS' BEHAVIOR OBSERVATIONS AT AREAS OF CROSSWALKS, ON-SITE STUDY

3.1. Pedestrians' characterization, on-site observation study

Almost 7 000 pedestrians' naturalistic behaviors (56% female and 44% male) at the area of zebra crossing were recorded in an on- site field study and then analyzed in detail. On-site study behaviors of pedestrians approaching and entering the crossing were analyzed in accordance with the scope of previous years' research for comparative, trend-tracking purposes. Selected characteristics of traffic and pedestrian' behaviors, including the average speed of pedestrians at crossings and loss of pedestrian time, were the focus of the research. Pedestrian safety assessment in terms of these parameters was performed with respect to crossing facilities located in different types of areas (cities, small towns, outside built-up areas) and signalization: with or without traffic lights, type of road section (on or not at junction) and different numbers of lanes on carriageway/ road cross sections with or without refuge areas (1x2, 1x4, 2x2, 2x3).

During the study of pedestrian' behaviours on crosswalks, indicators of the loss of pedestrian time and pedestrian' speed were used to assess their safety. Definition of pedestrian time loss (expressed in seconds) was defined as time pedestrian is waiting for the possibility of crossing before entering the carriageway. Speed of one pedestrian from the group was measured and registered. Pedestrian' speeds

and time losses on all crosswalks were average arithmetic of individual measurements for each indicator. Recorded video material enabled analysis of pedestrians' risky behaviours such as red-light crossing, crossing the roads outside designated pedestrian crossings, use of mobile phones (including writing Text messages and listening to music) while crossing.

The collected data showed that:

- the average speed of pedestrians at zebra crossings regardless of the type of road cross section was 1,3-1,4 m/s,
- the average pedestrian time loss at zebra crossings in built-up areas was 7, 9 s, which is considerably less than those outside built-up areas (14, 8 s). Average losses of pedestrian time on single carriageway were 8, 3 – 8 and 4 s, and were much less than those on dual carriageways (13, 9 s),
- average time losses of pedestrians indicated that pedestrian over 60 years old waited longer than younger before entering the carriageway at crossings outside built-up areas and on wide crossroad section of single carriageways of 1x4 and dual carriageways of 2x2 or 2x3 (Fig.6) [12].

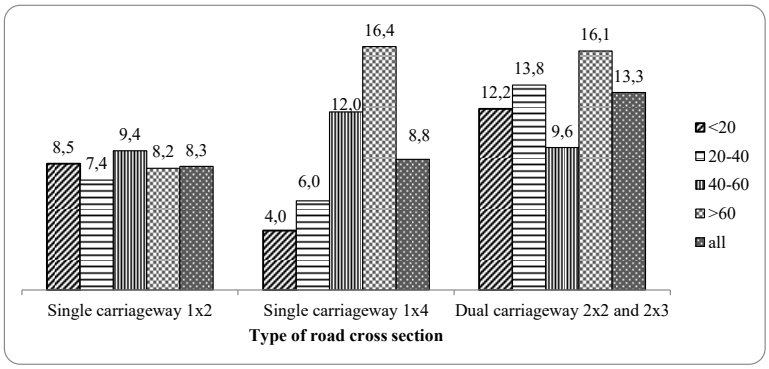

Fig. 6. Average time losses of pedestrians at all zebra crosswalks according to age [12]

Pedestrians approaching the crossing usually looked around and checked the situation before crossing the road. At each observed on-site crossing encounter, interactions between pedestrians and vehicles were analyzed according to one of two categories: the pedestrian approached the zebra crosswalk, stopped on the sidewalk and gave way to vehicles, or the vehicle stopped and gave way to the pedestrian. Recordings at on-site study locations (except for signalized crossings) showed that when a vehicle approached the crossing, on average, 55% of pedestrians stopped and waited for the opportunity to cross (vehicles would pass or some drivers stopped the car to give way to the pedestrian). 45% of pedestrians approaching zebra crossings were given way by the first oncoming vehicle so that they could cross the road without waiting. Analysis of driver–pedestrian encounters according to the age of pedestrians approaching zebra crosswalks showed that drivers relatively more often gave way to younger people. Older people waited longer on the sidewalks before crossing. This corresponds to pedestrian behavior while approaching the zebra crossing. Behavior of younger people (body language) more clearly indicated the intention to cross the road, they were more resolute and did not hesitate. Most older people (66%) over 60 years of age, who were more conservative, stood in front of the crossing on the sidewalk, waited until the vehicle came to a complete stop and gave way to them (Tab. 2). Research showed that this group of road users is the most careful, but statistically represents the highest number of injuries. Elderly aged 65 years and older in Poland and in the rest of European Union are the biggest group of pedestrians killed on road [2].

Observation of pedestrian' behaviours at the area of zebra crosswalks, in particular, driver–pedestrian interactions, showed that encounters vary depending on the type of crossing. Behaviours depend on the location of the crossing, and the volume of pedestrian and vehicle traffic. The greater the volume of pedestrian traffic in residential area was, more drivers stopped to give a way at non signalized zebra crossings. The most common (8%) violation observed was crossing at an unpermitted location up to 100 m distance from the designated zebra crosswalks. These behaviors were observed more among older pedestrians, that is, those older than 60 years of age (Tab. 3). These behaviors were usually observed in estate areas, where there is heavy pedestrian traffic and relatively low vehicle speed. Such behaviours

were not observed at pedestrian crossings on roads with more road lanes and where the permitted speed of vehicles was higher. Video-based behavioural data of driver-pedestrians encounter at area of crosswalks showed low number of drivers stopping sharply and suddenly for risky pedestrian unexpected entry. While crossing the road, 5% of pedestrians used mobile phones, more rarely wrote Text messages or wore headphones (Tab. 4).

Table 2

Pedestrian' behavior at zebra crosswalks [12]

Pedestrian age	Standing in front of the crossing on the sidewalk, giving way to vehicles (N=4 708)	
	Number	Percent
<20	289	52%
20-40	1071	49%
41-60	726	61%
>60	519	66%
Total	2612	55%

Table 3

Hazardous pedestrian behaviors at the area of zebra crosswalks [12]

Pedestrian' age	Red – light crossing (N=1400)		Crossing at an unpermitted location (N=6673)		Unexpected entry into the road (N=6108)	
	Number	Percent	Number	Percent	Number	Percent
<20	21	11%	77	9%	5	0,62%
20-40	49	8%	274	9%	13	0,48%
41-60	19	5%	153	9%	6	0,39%
>60	10	4%	64	6%	2	0,19%
Total	99	7%	565	8%	26	0,43%

A descriptive analysis of pedestrian behaviors to create a model of their behaviours was carried out with respect to age only. Hazardous pedestrian behaviors: red-light crossing at signalized zebra paths, as well as crossing outside designated pedestrian zebra paths 100 meters from the crossing and unexpected entry into the road and use of mobile phones in the area of crossing facilities were only categorized according to the age of the pedestrians. The sample collected at the area of crossing facilities was large enough (from 1400 to 6800) to define hazardous pedestrians' behaviors with respect to age. Collected data from observation on pedestrians' behaviours showed: 7% of pedestrians crossed on red-light signalization, 8% at not permitted location and 5% made conversation or used mobile phone while crossing zebra path. Due to the small number of risky pedestrians behaviours was not performed another analysis in respect to type of road cross section (1x2, 1x4, 2x2, 2x3), area (cities, small towns, not built-up areas) and road section (on/ outside junction).

Table 4

Hazardous pedestrian behaviors of use of mobile phones in the area of zebra crosswalks [12]

Pedestrian age	Conversation on the mobile phone (N=6108)		Writing Text messages (N=6108)		Listening to Music with headphones on (N=6108)	
	Number of cases	%	Number of cases	%	Number of cases	%
<20	56	7%	30	4%	38	5%
20-40	164	6%	32	1%	29	1%
41-60	61	4%	10	1%	4	0%
>60	10	1%	0	0%	1	0%
Total	289	5%	72	1%	73	1%

3.2. Driver behavior, on-site observation study

To determine vehicle traffic characteristics in the area of pedestrian crossings, vehicle speeds of 100 m before crossing and 10 m behind crossing were measured. Over 32 000 vehicles were tested. The vehicle speed was recorded when a vehicle appeared in the measuring section of the area of the pedestrian crossing when

- there was no pedestrian,
- the pedestrian was approaching the crossing (observation area up to 5 meters from the crossing),
- the pedestrian was waiting to cross the road,
- the pedestrian was entering the road and
- the pedestrian was at the crossing.

Recorded data of speed measurements at zebra crosswalks were separately analyzed for permitted speeds of 50 km/h and 70 km/h for large cities, small towns, and non-built-up areas. It was found that in areas with a speed limit of 50 km/h (located in cities and small towns), approximately 85% of drivers exceeded the speed limit, and at 10 m before pedestrian crossing, approximately 10% of drivers exceeded the speed limit (Fig. 7).

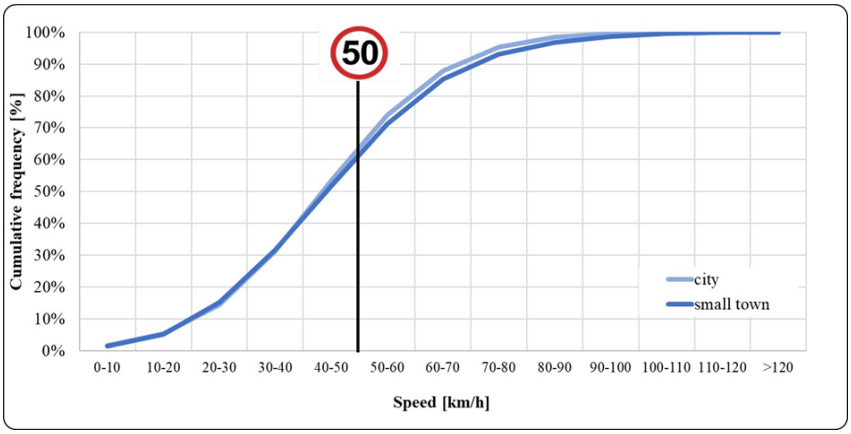

Fig. 7. Distribution of a speed of 10 m before a pedestrian crossing in cities and small towns – V limit = 50 km / h [12]

At non-built-up areas on roads with a speed limit of 70 km/h, 90% of drivers exceeded the speed limit, and at 10 m before a pedestrian crossing, approximately 68% of drivers exceeded the speed limit (Fig. 8).

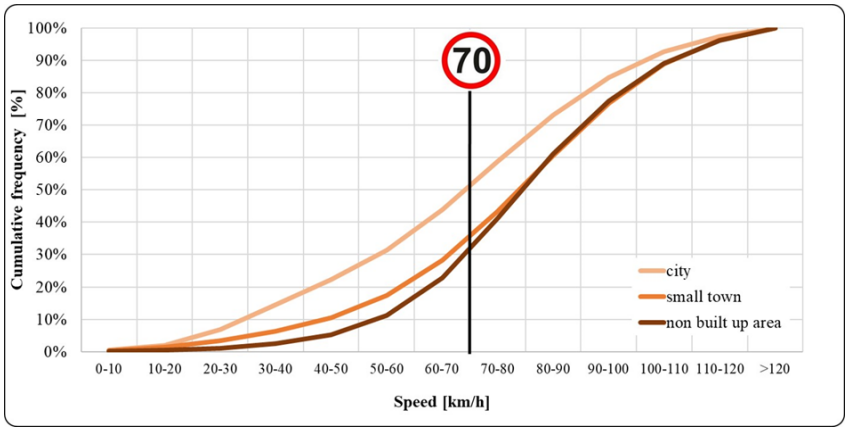

Fig. 8. Distribution of a speed of 10 m before pedestrian crossings in built-up areas and small towns - Vlimit = 70 km/h [12]

Other observed hazardous driver' behaviours at pedestrian crossing showed: 1.3% of drivers before zebra failed to stop what made pressure on pedestrian fully entered crosswalks; 0.3%, braked sharply in

front of the pedestrian and 0.03% of drivers drove at the red-light signalization. The results of the research showed that:

- in areas with permitted speed of 50 km/h there was observed the highest speed of vehicles in a distance of 10 m before marked pedestrian crossings at road cross section of dual carriageway with two lanes (2x2) or dual carriageway with three lanes (2x3) (Fig. 9).

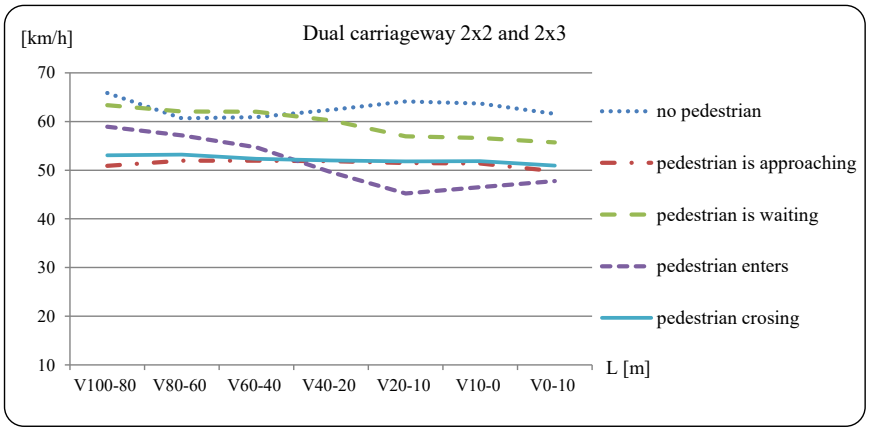

Fig. 9. Vehicle speed characteristics in the area of pedestrian crossings - permitted speed 50 km/h –average speed [12]

- in areas with a speed limit of 70 km/h there was observed the highest speed of vehicles in a distance of 10 m before marked pedestrian crossings at road cross section of single carriageway (1x2) without refuge island (Fig. 10),

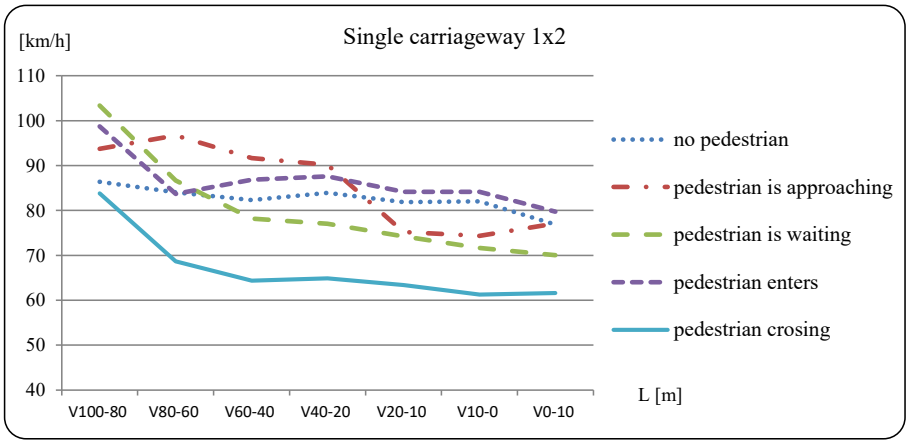

Fig. 10. Characteristics of vehicle speed in the area of pedestrian crossings - permitted speed 70 km/h - average speed at a distance up to 100 m before and up to 10 m after the pedestrian crossing [12]

- speeds on cross sections of all roads were lower while the pedestrian was waiting to cross than where there was no pedestrian,
- lower speeds of vehicles were measured in areas of intersections (permitted speed of 50 km/h and 70 km/h) at a distance of up to 10 m before a pedestrian crossing. The lower speed of vehicles in these areas was probably associated with the fact that drivers paid more attention to other vehicles than pedestrians, and while approaching the intersection, they were extremely cautious,
- drivers lowered their speed on all types of road cross sections at the distance 100 m before marked zebra crosswalks while pedestrian was approaching, then where there was no pedestrian. Vehicle' speed reduction was bigger on single than on dual carriageways (Fig. 11).

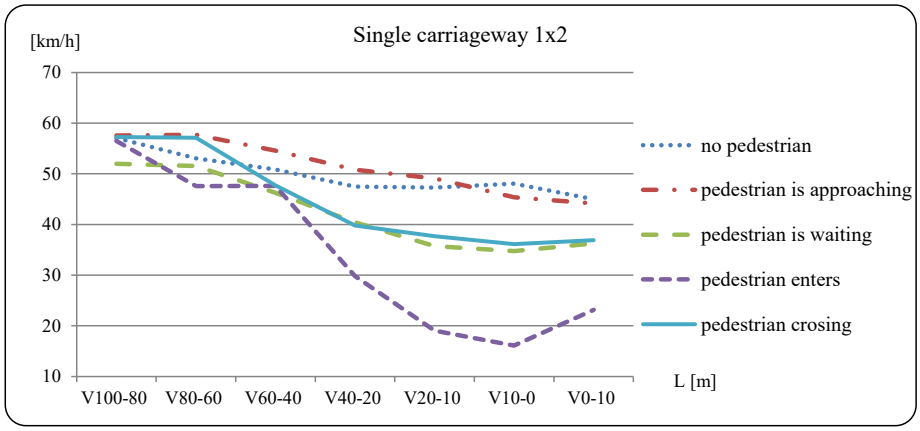

Fig. 11. Vehicle speed characteristics in the area of pedestrian crossings - permitted speed 50 km/ h - average speed at 100 m before and up to 10 m after the pedestrian crossing [12]

4. CONCLUSIONS

Performed observation study on pedestrian behaviors and pedestrian–driver encounters enabled the characterization of pedestrian and vehicular traffic. Results presented in the article showed risks to pedestrians crossing marked zebra crosswalks. In Poland, according to the statistics, 11% of accidents with pedestrians happened here together with 9% fatalities and 12% seriously injures.

Survey on road users' behaviors together with video-recorded driver–pedestrian encounters allowed assessment of the safety of vulnerable road users in pedestrian crossings in Poland in 2018. Analysis of recorded video material from on-site field observations clearly showed increased possibilities to assess road safety at zebra crossings. This type of analysis usually involves statistical data on road accidents. However, this time, a more comprehensive method of research to assess the safety of pedestrians was used (both statistical and video-recorded observations in real traffic) to identify the real risks and enable formulation of countermeasures.

Analysis of collected research material showed that vehicles in pedestrian crossings passed at high speeds. In cities and small towns, approximately 85% of drivers exceeded the speed limit of 50km/h and at 10m before pedestrian crossings, approximately 10% of drivers exceeded the permitted speed. At – non-built-up areas on roads with a speed limit of 70 km/h, 90% of drivers drove at speeds over the limit, and at 10 m before pedestrian crossings, approximately 68% of drivers drove faster. This poses a huge risk to pedestrians who want to cross the road safely. A survey of drivers' opinions (attitudes) confirmed that drivers knew the traffic rules, but did not follow them on the road.

Characteristics of pedestrians' behaviours at the area of zebra crossing in 2018 showed risky performance of not permitted location crossing in a distance of 100 meter from marked zebra crossings, mostly by older pedestrians aged 60+ years. They usually waited on the sidewalks in front of the zebra crossing, giving way to oncoming vehicles, and hesitated to enter the street. According to the pedestrians' survey, they confirmed both knowing and following traffic rules in practice. There were no conflict situations between pedestrians and drivers (unexpected entry into the road), or aggressive behaviors.

Observations during the on-site study showed that on some types of crossings, drivers behaved properly and correctly, giving way by stopping near almost every pedestrian approaching the zebra crossing. Locations of these crosswalks were on narrow streets, where there was both heavy pedestrian and vehicle traffic, usually at urban estate areas. Drivers moving at low speeds had the opportunity to observe the crosswalk and its surroundings to react appropriately when the pedestrian appeared. At low vehicle speed, pedestrians felt safer and could enter the crossing; their behavior was more predictable.

In conclusion, some countermeasures can be recommended for implementation at zebra crosswalks to improve safety of pedestrians:

- intensify efforts to reduce the real speed of vehicles near pedestrian crossings, particularly in residential areas, small towns, by expanding enforcement (control and supervision) and introducing infrastructure solutions for traffic calming (bumps, raised pavement areas, street closures, surface texture/ visual devices).
- avoid locations of pedestrian' crossings on roads where permitted speeds are above 50 km/h.

As a main countermeasure after this research, a new law to improve pedestrian safety at zebra crossings was introduced in Poland from June 2021. According to the new rule, drivers must stop the car to allow pedestrians approaching zebra crossings to cross safely. The results of this research, as a 'before' study, will allow comparison of future research using the same methodology. Comparison of the results would show whether introducing new regulations changes the behaviour of drivers who are now obliged by law to stop when a pedestrian approaches the sidewalk with the intention of crossing the street. Changing law should improve safety of pedestrians in the future, as today Poland has very high number of killed on crosswalks. There are 21 deaths of pedestrians per million populations in Poland, in European Union 10. It is expected to reduce the risk to pedestrians at no signalized crossings outside intersections and at no signalized intersections when the vehicle is turning right and when pedestrian is crossing the road at the exit or the entry of the crossing. This article presents the results of on-site behavioural observation study at the area of zebra crossing with characterization of driver-pedestrian's' encounters across Poland in 2018.

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