Keywords: drivers' speed behavior; average speed; pedestrian crossing; additional lighting system

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SPEED ANALYSES AND MODELING IN PEDESTRIAN CROSSING AREAS

Summary. The safety of vulnerable road users, especially pedestrians, on Polish roads remains among one of the lowest levels among EU countries. A high number of accidents involving pedestrians occur in areas with zebra crossings, and excessive speed is often mentioned in police records as a leading cause of accidents. A number of investigations highlight that drivers' speed strongly influences the impact on pedestrian safety; hence, it should be controlled in areas with pedestrian crossings through effective management. According to traffic law regulations, drivers are required to give special attention and slow down while approaching a pedestrian crossing. The aim of the article is to explore drivers' speed behaviors at zebra crossings depending on their localization. Investigated zebra crossings were located on single and dual carriageways on straight segments and approach sections of intersections without traffic lights. Speed measures were performed under free-flow traffic conditions. The conducted analysis allowed for the identification of road geometry-related parameters significantly influencing vehicles' speeds at pedestrian crosswalk locations. Based on the analyzed parameters, regression models were developed and validated.

1. INTRODUCTION

More than 1.3 million people die in road accidents every year around the world. In addition, up to 50 million people suffer from physical or psychological after-effects. According to the World Health Organization, excessive speed is on the list of the top five factors related to road crashes [1]. In Europe, according to accident statistics, excessive speed is a dominant factor leading to road accidents, and pedestrians represent about 22% of all road fatalities. Statistics demonstrate that pedestrians, bicyclists, and motorcyclists are among the most vulnerable road users despite the fact that a significant reduction in fatalities in urban areas (36%) was observed in the EU from 2007–2016 [2]. The improving statistics result partly from global actions started in the previous decade, which has been called the decade of action for road safety. The successes were the basis for undertaking a similar initiative in the current decade, with the ambitious goal of further reducing the number of road traffic victims by at least 50% by 2030. A holistic approach to road safety requires a strategy built on five main pillars:

- road safety management, coordinated by governmental agencies;
- safer vehicles, including the implementation of car assessment programs and manufacturing vehicles giving better protection to drivers by implementing electronic systems supporting active and passive vehicle safety, as well as vehicles that will cause fewer injuries to others;
- safer roads and mobility, including the design of self-explaining and forgiving roads;
- safer road users, including (among other efforts) legislating and enforcing speed limits and developing educational programs to improve the behavior of road users;
- efficient post-crash activities.

Based on the proposed strategy, some short- and long-term courses of action were recommended. Those related to the direct impact on vulnerable road users focus on effective speed management. A

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lack of effective protection in a collision with a vehicle leads to serious injury or death due to the high-impact energy generated at a high speed. The probability of serious injury or death increases exponentially with speed, and accidents at higher speeds have more serious consequences. In accidents involving pedestrians, the risk of pedestrian death is directly related to vehicle speed. Correlations between the risk of pedestrian fatality and the speed at impact have been established (Fig. 1) [3]. By keeping vehicle speeds below 30 km/h, the likelihood of collisions between motor vehicles and pedestrians can be better controlled; moreover, if such collisions do occur, they are usually non-fatal. However, the average risk of fatal injury for a pedestrian hit by a vehicle reaches 75% at 62 km/h and 90% at 74 km/h [4].

In Poland, the safety of vulnerable road users has been a concern for decades. Despite numerous activities undertaken to improve the situation, the statistics show stagnation, especially in terms of the proportion of pedestrians killed in the total number of deaths. From 2011–2020, the proportion of pedestrians killed in road accidents ranged from 25 to 30% of all road accident victims each year and remained almost unchanged. In addition to the issue of the geometry of pedestrian crossings, issues related to the improvement of visibility conditions are also emphasized. In a holistic approach to road safety, road accidents are analyzed as a result of many factors related to road infrastructure and environmental conditions, as well as vehicle and driver characteristics. However, one of the main problems in terms of road safety remains excessive speed and unsafe driver behaviors [5–8]. The high speeds at which most car drivers approach and go through pedestrian crossings remain an unresolved issue. Moreover, every year 3,500 road accidents are recorded at pedestrian crossings, which accounts for 49.5% of all accidents involving pedestrians.

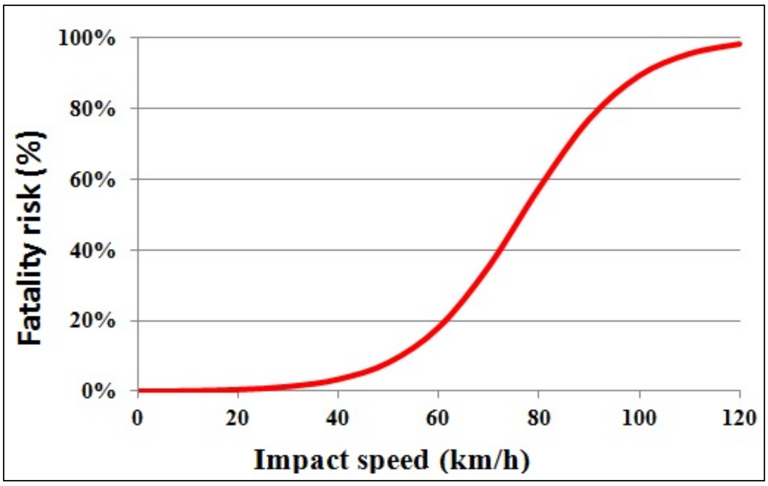

Fig. 1. Probability of pedestrian death risk as a function of impact speed [3]

Investigations of pedestrian-vehicle conflict have underlined multiple interactions and numerous factors influencing occurring conflicts: pedestrian characteristics, road and traffic conditions, and environmental factors in the area of crosswalks [9–10]. Yagils's investigations [11] of pedestrians' characteristics led to the conclusion that men are less aware than women of their conflicts with vehicles while crossing the street. Considering pedestrians' age, Liu and Tung [12] revealed that elderly pedestrians exposed themselves to a higher level of risk than young pedestrians due to their lower moving speed.

To effectively manage vehicle speed, traffic calming measures have been introduced, especially in urban areas. Their application is intended to keep drivers' speed under a certain limit that is safe for vulnerable road users and to reduce the frequency and severity of accidents. Basic implementations include law enforcement, vertical chicanes, horizontal chicanes, and education activities, of which physical measures are the most effective. The most effective measures are the implementation of various physical chicanes; however, their installation is mostly limited to urban areas due to travel speed.

However, in some cases, selected physical measures can be installed in the transition zones between non-urban and urban areas. Preferably, these are raised crosswalks, entry gates or horizontal deflections. In Poland, the influence of central islands on vehicle speeds and accident reduction was confirmed in studies conducted by Sołowczuk and Kacprzak [13]. The results showed reductions in the average speed and number of road incidents.

Harwood et al. [14] analyzed vehicle-pedestrian accidents at signalized intersections in Toronto, Canada. As a result, they developed a crash predictive model that included a higher traffic volume, pedestrian intensity length of the crossing considering the presence of refuge islands, and the presence of bus stops in the nearest area of the intersection. Similar factors were also found by Chen et al., who conducted research in Beijing, China [15].

Research conducted for unsignalized intersections [16] allowed pedestrian crash risk to be combined with crossing length, the presence or absence of refuge islands, and the number of lanes. After analyzing multi-lane road crosswalks on higher volume roads, the authors recommended enhancing nighttime lighting and reducing the number of lanes to improve pedestrian safety. Among several factors that can affect the risk of pedestrian involvement in crashes, speed remains one of the most important. Designing safe and comprehensive facilities for pedestrians is vital to reducing the frequency of pedestrian crashes. However, knowledge of drivers' speed behavior is crucial because it can help create the basis for undertaking effective actions aimed at increasing the level of pedestrian safety.

The target of this research is to explore drivers' travel speed at locations of unsignalized crosswalks and relate it with pedestrian crossings' geometric parameters to propose linear regression models for predicting the average speed and 85th percentile speed at the crosswalk locations.

2. TEST SITE CHARACTERISTICS AND SPEED MEASUREMENTS

The research area included 17 unsignalized pedestrian crossings located in the city of Bialystok (Fig. 2), Poland, of which 11 are located on single-carriageway roads (PC_1 to PC_11). The other six are situated on dual carriageway roads (PC_12 to PC_17). The analyzed single-carriageway roads consist of two lanes (one in each direction), while the dual-carriageway roads' cross-sections consist of four lanes (two lanes in each direction). The investigated zebra crossings are located in mid-block segments and inlet sections of intersections without traffic lights. The areas of the analyzed crosswalks have various speed limits. Along the single carriageways, the posted speed limits are 30 km/h, 40 km/h, and 50 km/h. Along the dual carriageways, the speed limits are 70 km/h and 50 km/h. The geometric characteristics of the zebra crossings and instantaneous speed parameters are presented in Table 1 (single-carriageway roads) and Table 2 (dual-carriageway roads). Speed measures were carried out for three months (September-November 2019) using a speed gun at pedestrian crossings. Free-flow driving conditions were ensured by taking measurements when there were no pedestrians in the area of the crosswalk and when the distance between vehicles (including those in the opposite lane) was at least 100 m. Measurements were performed during off-peak periods in the daytime. The number of vehicles recorded at each crosswalk was at least 120. In the case of pedestrian crossings located on approach sections of intersections, only vehicles moving straight ahead were recorded.

3. METHODOLOGY FOR MODEL DEVELOPMENT

Statistical models for predicting the average speed (V_{avg}) and the 85th percentile speed (V85) were developed by employing multiple regression to correlate the dependent variables with the selected geometrical parameters of the road (independent variables). The Fisher-Snedecor test was used to verify the significance of the model, and the p-value of the F statistic was set at 0.05 (95% confidence). The individual significance of each coefficient was tested using Student's t-test. For the linear regression model, some assumed hypotheses were verified regarding a linear relationship, the collinearity of variables evaluated by variables tolerance, and the variance inflation factor (VIF) [17]. The goodness of fit of the model was assessed based on the plots of the observed data vs. predicted data.

Fig. 2. Locations of analyzed pedestrian crossings

Table 1

Basic geometric and speed characteristics at investigated crossings located on single carriageways

Pedestrian crossing	Lane width	Pedestrian length*	Speed limit	V_{avg}	V15	V85	% Speed	SD
	[m]	[m]	[km/h]	[km/h]	[km/h]	[km/h]	[%]	[-]
PC_1	4.0	10*	30	37.7	32.0	43.3	97.0	6.62
PC_2	3.5	7.0	40	39.3	35.0	45.3	35.0	4.99
PC_3	3.7	9.4*	40	45.0	38.8	51.2	80.0	6.05
PC_4	4.35	8.7	40	53.9	44.7	61.8	97.0	8.62
PC_5	3.4	6.8	40	40.2	33.2	46.8	40.0	6.88
PC_6	3.5	9.0*	40	46.7	36.4	57.7	34.0	9.28
PC_7	3.75	9.5*	50	56.9	52.0	63.2	92.0	5.67
PC_8	4.0	10.0*	50	55.6	50.0	63.3	82.0	6.32
PC_9	3.5	7.0	50	55.2	49.0	61.0	70.0	7.34
PC_10	4.0	10*	50	47.8	39.2	55.0	72.0	8.29
PC_11	3.7	7.4	50	53.1	47.0	59.0	58.0	6.72

* Includes a refuge island

Table 2

Basic geometric and speed characteristics at investigated crossings located on dual carriageways

Pedestrian crossing	Lane width	PC total length*	Median strip	Speed limit	V_{avg}	V15	V85	% Speed	SD
	[m]	[m]	[m]	[km/h]	[km/h]	[km/h]	[km/h]	[%]	[-]
PC_12	3.25	15.5*	2.5	70	76.9	69.9	86.0	83.0	7.42
PC_13	3.5	17.0*	3.0	50	57.5	52.9	63.0	98.0	4.70
PC_14	3.5	22.0*	5.0	50	50.6	42.8	58.3	48.0	8.39
PC_15	3.5	29.0*	15.0	50	51.5	45.9	57.2	40.0	6.70
PC_16	3.5	19.0*	5.0	50	51.7	46.0	58.0	53.0	5.46
PC_17	4.0	22.7*	6.7	50	50.5	44.0	57.2	35.0	7.36

* Includes a median strip

4. RESULTS AND DISCUSSION

Considering the results of the average speed values achieved on pedestrian crossings located on single carriageways (Fig. 3), it can be observed that drivers do not generally obey speed limits regardless of the limit itself. The highest difference between the average speed and the speed limit was recorded on the road with the lowest limit of 30 km/h (25.7%). The lowest difference was recorded on roads with a speed limit of 50 km/h; in this case, the average speed was only 7.4% over the limit. Considering the average speed, its relation with the posted speed limit is quite clear, and a higher posted speed limit encourages drivers to drive faster. The average speed on streets with V_{lim} = 50 km/h is 19.3% (8.7 km/h) higher than the average speed on streets with a speed limit of 40 km/h and 42.4% (16.0 km/h) higher than on streets with a 30 km/h speed limit. The highest percentage of violating drivers (97.0%) recorded on roads with a speed limit of 30 km/h further highlights the inefficiency of speed control by means of only road signs without any additional physical means. On streets with speed limits of 40 km/h and 50 km/h, the percentages of violating drivers were 40% and 22.2% lower, respectively. Another factor conducive to excessive speed is lane width. This was also observed in the case of higher speed limits – wider travel lanes were associated with higher numbers of speeding drivers. In the case of pedestrian crossings located on streets with travel lane widths of 3.4 m and 3.5 m, the percentage of violating drivers was distinctly lower than for crossings on other streets.

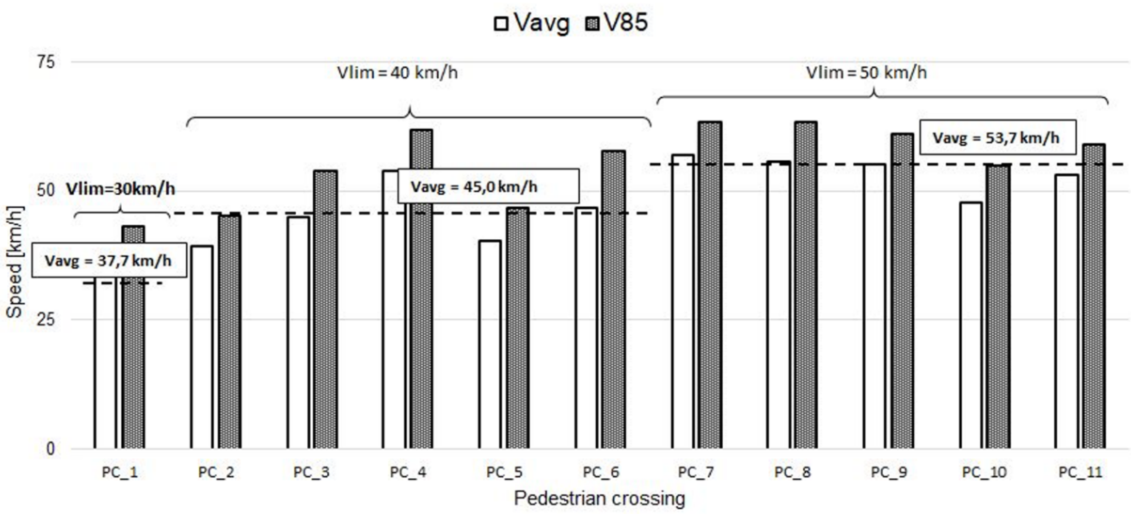

Fig. 3. Average speeds on pedestrian crossings: Single carriageway roads

An analogous tendency with an even higher difference in average speeds was observed in the case of pedestrian crossings situated on dual carriageways (Fig. 4). Favourable driving conditions on dual carriageways prompt drivers to drive faster. The average speed on crosswalks located on dual-carriageway roads with a 50 km/h speed limit was 16.4% (7.4 km/h) higher on crosswalks located on single carriageways with the same speed limit. Moreover, the average speed on crosswalks located on roads with a 70 km/h speed limit was 46.8% (24.5 km/h) higher than the average speed recorded on crosswalks on roads with a 50 km/h speed limit. The data also revealed the problem of speeding drivers. This phenomenon is linked to the existing speed limit – the higher the speed limit, the higher the percentage of violating drivers. The behavior pattern of drivers on dual carriageways is opposite to that observed on single carriageways. A higher percentage of violating drivers (83%) was recorded on streets with a 70 km/h speed limit than on streets with a speed limit of 50 km/h (54%). The opposite pattern was observed on single-carriageway roads. On dual-carriageway roads, there was no clear relationship between the number of violating drivers and the width of the lane. However, the median strip width had an influence, as the percentage of violating drivers decreased as the median strip width increased.

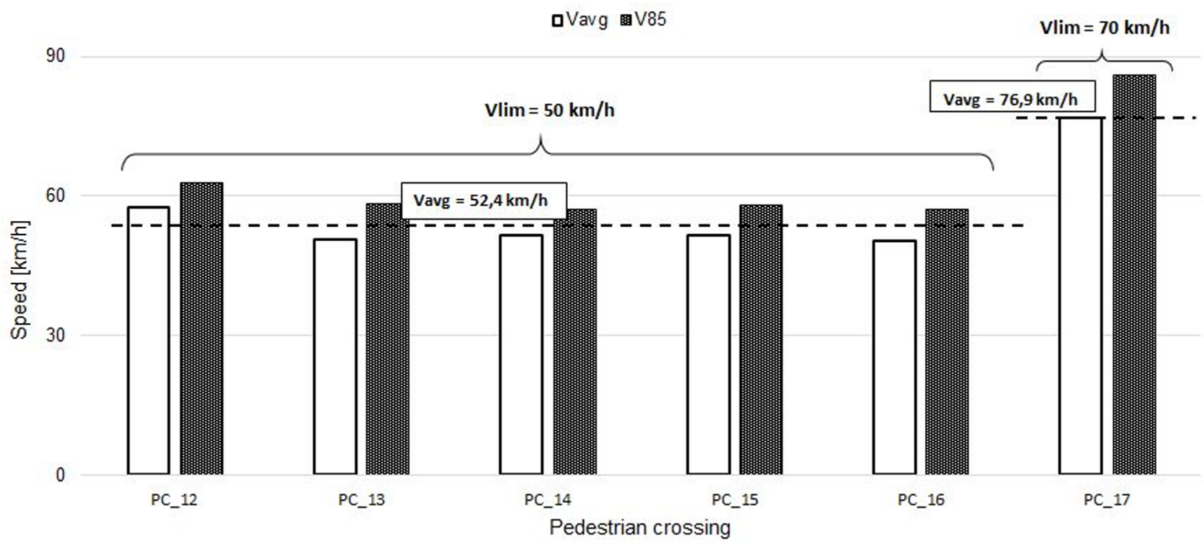

Fig. 4. Average speeds on pedestrian crossings: Dual carriageway roads

The aforementioned analyses lead to the conclusion that in the vast majority of studied cases, the average speed exceeded the speed limit, regardless of the cross-section of the road. In addition, in the case of single carriageways, drivers are not likely to adjust their speed to a lower speed limit if, from their perspective, road conditions encourage higher speeds.

The results of speed heterogeneity (Fig. 5) by means of the ratio of speed uniformity R_{SU} (expressed as the difference between speed parameters V85 and V15 referring to the posted speed limit) show a relationship between the speed limit and speed uniformity. The highest speed heterogeneity was recorded at crosswalks situated on single-carriageway roads with a speed limit of 40 km/h. The average speed differences computed within pedestrian crossings situated on single-carriageway streets with a speed limit of 40 km/h reached 44% but was only 23% in the case of dual carriageways with a speed limit of 70 km/h. Recorded high-speed variations can be explained by a large difference in drive lane width and less uniform driving conditions (the presence or lack of a refuge island). This inhomogeneity is further supported by the fact that the highest standard deviation values were recorded on streets with a 40 km/h speed limit.

The results of the statistical analysis (Table 3) show a highly significant influence of considered geometric parameters on average speed. The p-value obtained in the analyses ($p<0.01$) is much lower than the original assumed significance level. The average values differ substantially in the scope of the analyzed variables. A sample graph showing the dependence of average speed on the speed limit is

presented in Fig. 6. The following explanatory variables were used to develop linear regression models for dependent variables (V_{avg}, V85):
- speed limit, lane width, total pedestrian crossing length (for pedestrian crossings located on single carriageways)
- speed limit, lane width, median strip, and total pedestrian crossing length (for pedestrian crossings located on dual carriageways).

The proposed model for predicting the V_{avg} at a pedestrian crossing location is shown in Equation (1):

$$V_{avg} = -18.87 + 0.874 \cdot V_{\lim} + 8.037 \cdot LW \,, \quad (1)$$

where V_{avg} is the average speed at the crosswalk's location, V_{lim} is the posted speed limit, and LW is the drive lane width.

Similarly, Equation (2) is proposed for predicting the V85 at a pedestrian crossing:

$$V85 = -8.33 + 0.80 \cdot V_{\lim} + 7.55 \cdot LW \,, \quad (2)$$

where V85 is the 85th percentile speed at the crosswalk's location, V_{lim} is the posted speed limit, and LW is a driving lane width.

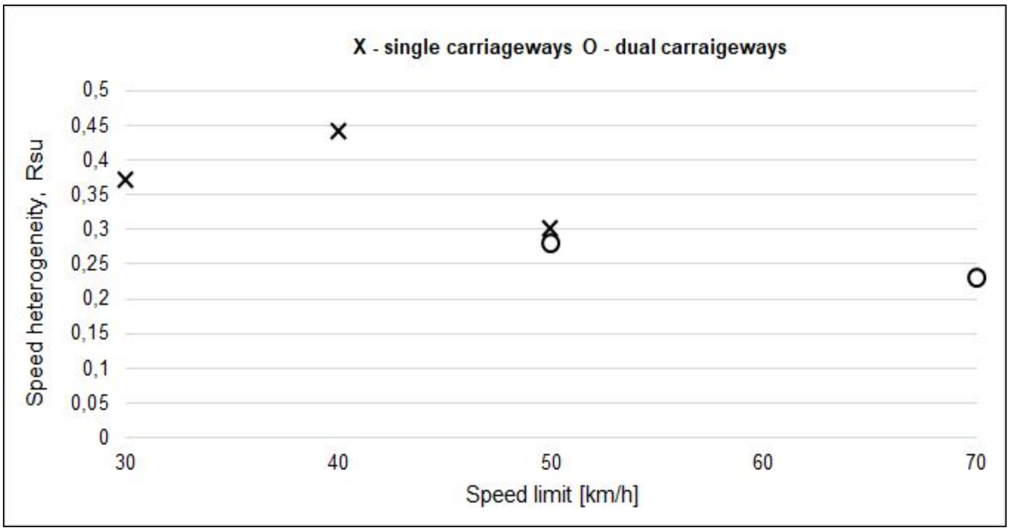

Fig. 5. Speed heterogeneity crossings: Dual carriageway roads

Table 3

Results of ANOVA for single and dual carriageways

Variable	SS effect	df effect	MS effect	SS error	df error	MS error	F	p
Single carriageways								
Speed limit	8558.28	2	4279.14	36612.5	467	78.39	54.58	<0.01
Lane width	9051.20	5	1810.24	39780.7	514	77.39	23.38	<0.01
PC length	9356.90	7	1336.70	33556.2	472	71.09	18.80	<0.01
Dual carriageways								
Speed limit	20032.8	1	20032.8	12162.0	238	51.10	392.0	<0.01
Lane width	20210.5	2	10105.2	11984.7	237	50.56	199.8	<0.01
Median strip	21389.5	4	5347.37	10805.7	235	45.98	116.2	<0.01
PC length	21412.6	5	4282.52	10782.6	234	46.07	92.93	<0.01

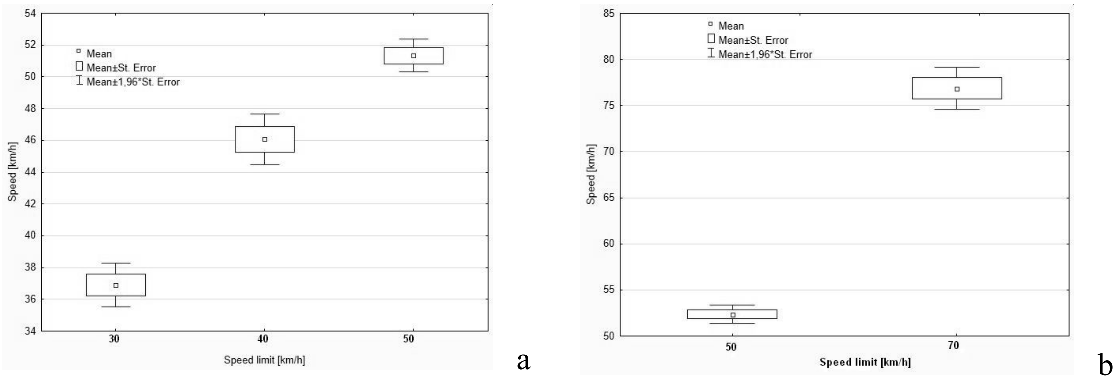

Fig. 6. Box plots of average speeds in relation to the speed limit on a) single carriageways and b) dual carriageways

In the case of dual carriageways, the developed models predicting V_{avg} and V85 include additional significant variables—median strip and pedestrian crossing length—which allowed the models to explain at least 98% of the dependent variable (Table 6 and Table 7):

$$V_{avg} = 35.366 + 0.955 \cdot V_{\lim} - 4.617 \cdot LW - 0.395 \cdot MS - 1.440 \cdot PL \tag{3}$$

$$V85 = 21.137 + 1.175 \cdot V_{\lim} - 3.721 \cdot LW - 0.353 \cdot MS - 0.645 \cdot PL \tag{4}$$

where V_{lim} is the posted speed limit, LW is the drive lane width, MS is the width of the median strip, and PL is the pedestrian crossing length.

Figs. 7–8 show the plot of predicted values vs. observed values of the speed parameters for the models obtained at pedestrian crossings located on single- and dual-carriageway roads. Tables 4–7 present the ANOVA results of the models of Equations (1)–(4). As observed, all models are highly significant (p-value of the F-test below 0.05), and each of the coefficients of the variables and the intercept are statistically significant (all p-values obtained in the analyses are much lower than the assumed significance level).

The conducted analyses confirm the usefulness of the models obtained. The statistical significance of the models and included variables was verified. Determination coefficients R2 indicate a good fit of the linear regression functions to empirical data, especially in the case of dual carriageways. In the case of single carriageways, the variables included in Models (1) and (2) explain 74% of the variation in V_{avg} and 62% of the variation in 85th percentile speed. The increase of the posted speed limit by 10 km/h increased V_{avg} by 8.7 km/h, while a 1.0-m increase in drive lane width caused an increase in V_{avg} of 8.0 km/h. A similar relation was observed in the case of V85.

Table 4

Analysis of the Variance of the Model (Equation 1)

Source	Sum of squares	Degrees of freedom	MS error	F value	*p*-value	R	
Model	15552.2	2	77.76	658.21	<0.001	0.86	
Error	5517.1		11.81			Adj. R^2	
Corrected total	21069.4					0.74	
Parameter estimates						Colinearity statistics	
Variable	Parameter	Standard	t value	*p*-value		Tolerance	VIF
Intercept	-18.87	2.430	-7.757	<0.001			
Speed limit	0.874	0.025	33.813	<0.001		0.99	1.00
Lane width	8.037	0.570	14.097	<0.001		0.99	1.00

Table 5

Analysis of the Variance of the Model (Equation 2)

Source	Sum of squares	Degrees of freedom	MS error	F value	p-value	R	
Model	14453.7	2	7226.88	392.50	<0.001	0.79	
Error	8782.6		18.41			Adj. R^2	
Corrected total	23236.4					0.62	
Parameter estimates						Colinearity statistics	
Variable	Parameter estimate	Standard error	t value	p-value		Tolerance	VIF
Intercept	-8.33	2.991	-2.78	<0.001			
Speed limit	0.80	0.031	25.98	<0.001		0.99	1.00
Lane width	7.55	0.705	10.69	<0.001		0.99	1.00

Table 6

Analysis of the Variance of the Model (Equation 3)

Source	Sum of squares	Degrees of freedom	MS error	F value	p-value	R	
Model	20826.9	4	5206.7	1710.3	<0.001	0.98	
Error	715.41		3.04			Adj. R^2	
Corrected total	21542.4					0.97	
Parameter estimates						Colinearity statistics	
Variable	Paramet	Standard	t value	p-value		Tolerance	VIF
Intercept	35.366	3.147	11.23	<0.001			
Speed limit	0.955	0.021	44.84	<0.001		0.50	1.98
Lane width	-4.617	0.619	-7.45	<0.001		0.65	1.52
Median strip	-0.395	0.030	-13.05	<0.001		0.79	1.26
Pedestrian_length	-1.440	0.109	-13.15	<0.001		0.77	1.29

Table 7

Analysis of the Variance of the Model (Equation 4)

Source	Sum of squares	Degrees of freedom	MS error	F value	p-value	R	
Model	25337.7	4	6334.4	3939.8	<0.001	0.99	
Error	377.8		1.6077			Adj. R^2	
Corrected total	25715.5					0.98	
Parameter estimates						Colinearity statistics	
Variable	Parameter estimate	Standard error	t value	p-value		Tolerance	VIF
Intercept	21.137	2.287	9.23	<0.001			
Speed limit	1.175	0.015	75.89	<0.001		0.50	1.98
Lane width	-3.721	0.449	-8.27	<0.001		0.65	1.52
Median strip	-0.353	0.022	-16.01	<0.001		0.79	1.26
Pedestrian_length	-0. 645	0.079	-8.54	<0.001		0.77	1.29

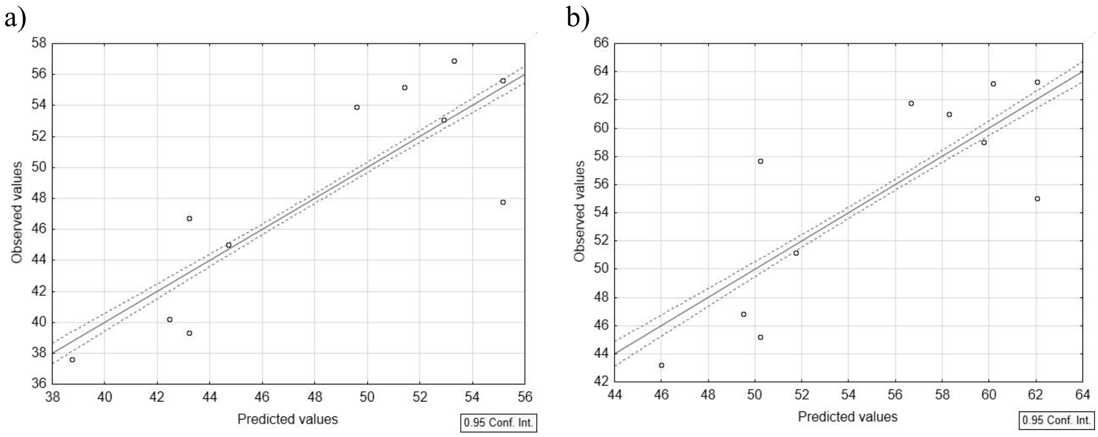

Fig. 7. Plots of the observed data vs. predicted data on single carriageways: a) Vavg and b) V85

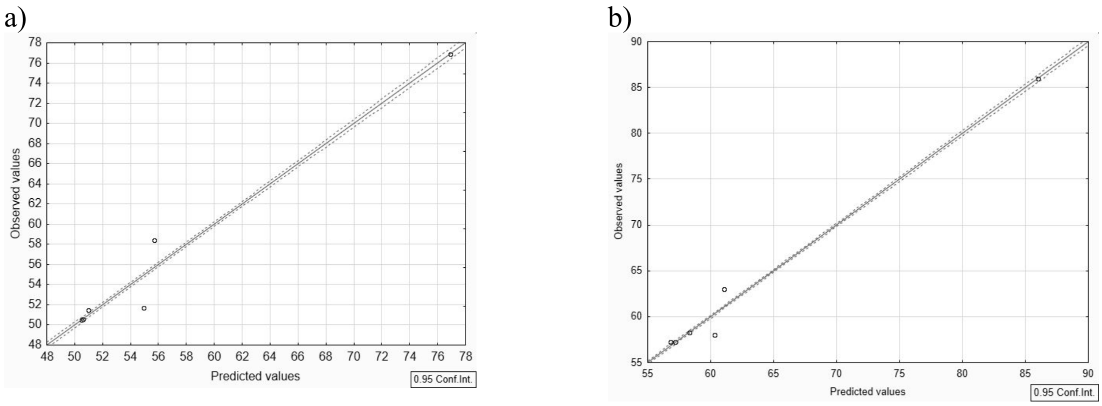

Fig. 8. Plots of the observed data vs. predicted data on dual carriageways: a) Vavg and b) V85

Models (3) and (4) describing V_{avg} and V85 on pedestrian crossings located on dual carriageways include additional significant variables: median strip and pedestrian length. Their inclusion allowed the models to explain the dependent variables at rates of 97% and 98%. However, opposite to Models (1) and (2), the increases in LW, MS, and PL result in decreases in V_{avg} and V85. The only variable positively correlated with the dependent variables is the speed limit—a 10 km/h increase caused increases in the average speed and 85th percentile speed of 9.5 km/h and 11.7 km/h, respectively. It is worth noting that the negative relationship between lane width and average speed contradicts the findings of other researchers [17–18] who have shown that vehicle speed increases alongside increases in lane and road width. However, their investigations devoted to cross-section factors did not include pedestrian crossings.

5. CONCLUSIONS

Excessive speed is a dominant factor leading to serious road accidents in which pedestrians account for more than 20% of all fatalities. Moreover, in Poland, road accidents recorded at pedestrian crossings constitute around 50% of all accidents involving pedestrians. However, there is scarce literature devoted to speed analysis in these particularly sensitive places. For this reason, speed data were collected at places of zebra crossings located on single and dual carriageways in the city of Bialystok. The average speed and 85th percentile speed were analyzed in relation to chosen geometric parameters: the posted speed limit, drive lane width, median stripe width, and crossing length.

The conducted analyses revealed that excessive speed remains a serious problem because most drivers do not obey the posted speed limits regardless of the cross-section of a road. The problem seems to be especially serious on single-carriageway roads on which the speed limit is lowered to 30 km/h (97% of all drivers exceed the speed limit on such roads). These results confirm that drivers' speed must be additionally managed, or more respect should be given to the design process.

On the other hand, the analysis of variance confirmed that the average speed and 85th percentile speed at places with pedestrian crossings depend significantly not only on the speed limit but also on the crosswalk's geometric parameters, such as the drive lane width, the crosswalk's length, and the width of the median strip. Using these parameters in regression analyses allowed the development of highly correlated linear models (R2 = 0.62÷0.98). The developed models can be useful for predicting V_{avg} and V85 as a function of the speed limit and the width of a drive lane for pedestrian crossings located on single carriageways. In the case of dual carriageways, the proposed models also included the median strip and the pedestrian length. The conducted analyses and the models obtained confirm that, already at the design stage, solutions can be introduced that will support better control of the excessive speed at which drivers travel. This is particularly important in high-risk areas such as pedestrian crossings without traffic lights.

These models can provide support for road infrastructure designers, especially in designing safer pedestrian crossings in terms of effective speed management at their sites.

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