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ROAD SAFETY RISK ASSESSMENT AT PEDESTRIAN CROSSINGS: A CASE STUDY FROM SUŁKOWICE

Summary. Pedestrians are vulnerable road users; therefore, they require special attention. In the pedestrian infrastructure, the greatest risk involves pedestrian crossings because they are the conflict points with vehicular traffic.

A method to assess pedestrian crossing infrastructure in terms of road safety is presented. The method involves observation of the associated infrastructure and environment, as well as measurements of vehicular and pedestrian behaviour.

The assessment involved 17 pedestrian crossings along a main road in the town of Sułkowice, Poland, with the aim of demonstrating the universality of the procedure. Only two of the crossings were found to have the lowest risk, while five were considered as high risk; none was assigned the highest risk score.

Keywords: risk assessment; pedestrian road safety; pedestrian crossing.

1. INTRODUCTION

Transport is an inalienable constituent of the development of human civilization. Since the 19th century, vehicular transport has become a dominant presence, while the number of vehicular journeys is constantly increasing. The majority of efforts are directed at improvements in the roadways for vehicular transport, but one must not forget about

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unprotected road users, amongst whom pedestrians are the most vulnerable. Indeed, pedestrians constitute a very significant proportion of victims of road accidents: in 2014, there were 1,079,800 vehicular accidents in the EU, resulting in the death of 5,772 pedestrians [1]. This high number of killed pedestrians is alarming because, in modern countries, the majority of traffic is along pavements. The riskiest places are those that involve traffic conflicts, namely, pedestrian crossings. Therefore, the presence of appropriate infrastructure is critical for protecting the safety of vulnerable road users.

Previously, it was found that the “safe” collision speed was only about 30 km/h [2]. As presented in Fig. 1, the risk to pedestrians does not increase linearly, but with some “kinks”, which may be attributed to the evolutionary development of human beings. Jamroz and colleagues [3] have recently presented the correlation between vehicle speed and the risk of injury to pedestrians, as shown in Fig. 1.

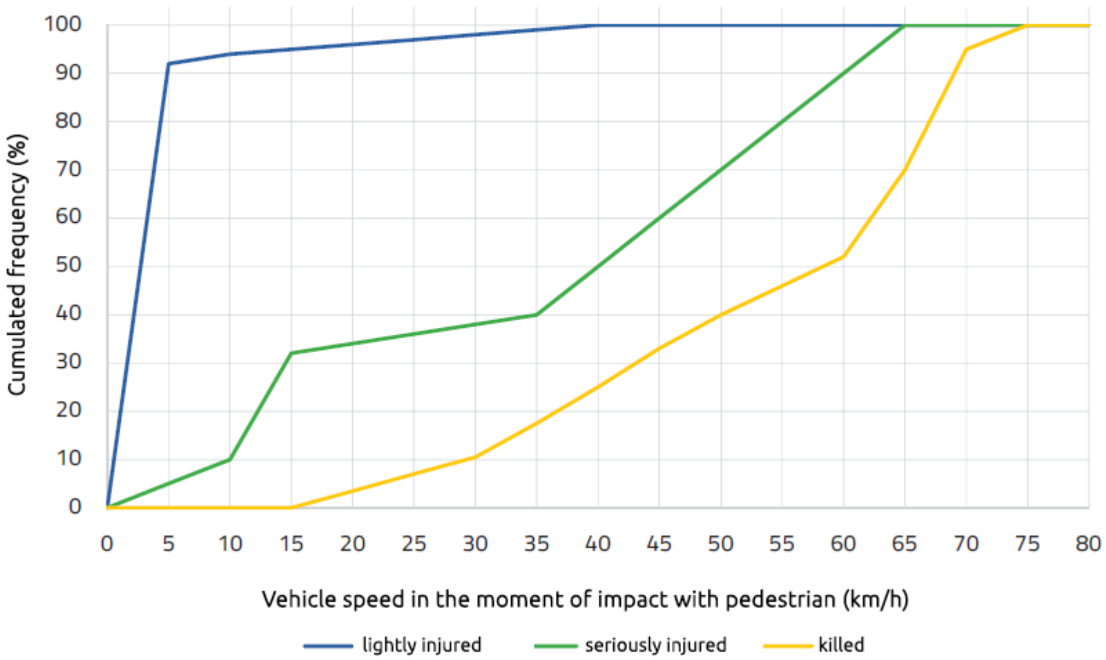

Fig. 1. Results of vehicle-pedestrian collision at various speeds: cumulative amounts (in percentages) of lightly wounded (blue), severely wounded (green) and killed (yellow) are shown

1.1. Purpose

The large number of collisions involving pedestrians has inspired research to assess the factors responsible for increasing and decreasing accident rates. The majority of vehicle-pedestrian accidents take place while pedestrians venture onto the roadway at points when and where they should not. However, the second most dangerous areas for pedestrians are marked crossings, over which road administrators having profound influence regarding their location and engineering controls to assure safe passage.

Herein, we provide an assessment of existing pedestrian crossings along a secondary road in a residential area to demonstrate the usefulness of our method. Amongst the analysed factors are (1) traffic load (both vehicular and pedestrian) and speed measurements, (2) visibility factors, (3) general infrastructure information, (4) safety-enhancing infrastructure, and (5) the behaviour of pedestrians and drivers.

This exploratory analysis may include not all of the factors needed for a perfect assessment. That said, at present, we are working towards improving the scoring system by adding additional parameters and eliminating some of the subjective evaluations.

1.2. Location

Sułkowice is a town with slightly over 6,500 inhabitants, which is located about 35 km south of Cracow, Poland. The town is mostly stretching along road number 956, a two-lane secondary (voivodeship) road with annually averaged daily traffic (ADT) of 9,877 vehicles (measured in 2015 between pedestrian crossings labelled 10 and 11 on Fig. 2) [4]. Over 90% of the 9,877 vehicles are passenger vehicles, with only 2.0% being lorries over 3,500 kg. The road is used for both local and transit traffic.

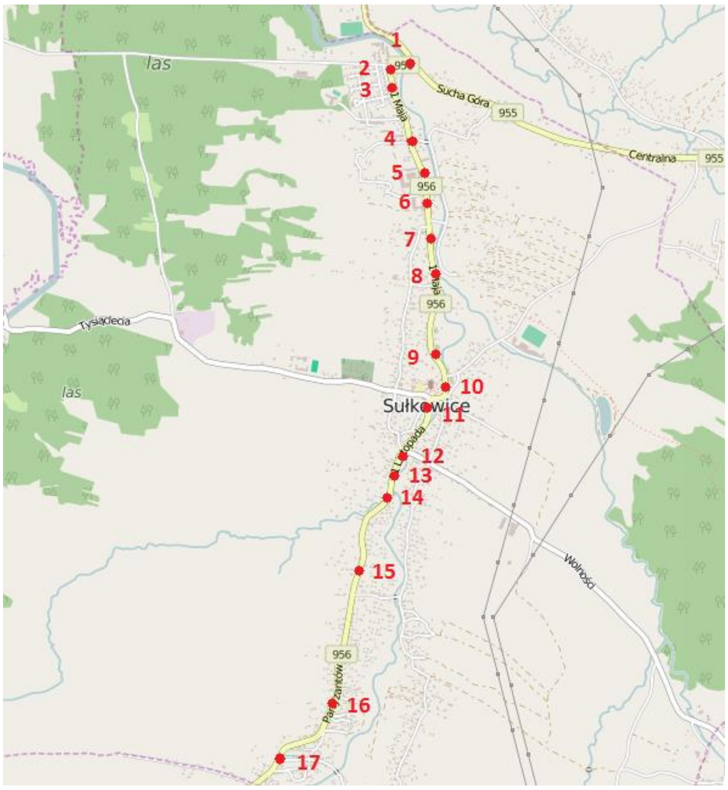

Fig. 2. Map of Sułkowice and location of the analysed pedestrian crossings.
Source: The authors, based on openstreetmap.org

The 17 marked pedestrian crossings along the road are identified in Fig. 2. All of the pedestrian traffic is at road level, while the street is equipped with kerbs and pavements; there are no separate bicycle pathways. The majority of the analysed crossings are located in the vicinity of intersections with local roads. Only one crossing (labelled ‘1’) is next to a major intersection. It must be noted that vehicular traffic is decreasing throughout the analysed area: an ADT of 4,338 vehicles was noted at the next analysed stretch, beyond Sułkowice (beyond the pedestrian crossing labelled ‘17’) [4].

1.3. Road safety statistics

The number of accidents in Poland is one of the highest in the EU. Numerous actions, starting with driver and road user education, improvement in the infrastructure and increased law enforcement led to a decrease in the number of those killed by 42% between 2002 and 2012. However, the risk still remains very high. Table 1 summarizes selected statistical data based on reports from the police [5] and statistics from the European Commission [1].

In comparison with the rest of Poland, Sułkowice may be considered as relatively safe in terms of traffic accidents: no persons were killed on the town roads in the analysed three-year period. This is an important observation because the town is located along a main road and there are numerous places where pedestrians must cross it. An additional insight allows for the analysis of the accidents' severity, in terms of the number of killed or injured per accident, which remains fairly constant in Poland; however, in Sułkowice, it has increased. These facts suggest that the imposed road safety methods are not sufficient. Due to the small sample size in Sułkowice and the relatively short analysed periods, such statistical analyses should be treated with caution.

Table 1. Road safety statistics in Sułkowice and in Poland

Area	**Sułkowice**			**Poland**		
Population	6,537			38,478,602		
Accidents						
Year	Number	Per 1,000 inhabitants		Number	Per 1,000 inhabitants	
2012	6	0.92		37,046	0.96	
2013	9	1.38		35,847	0.93	
2014	7	1.07		34,970	0.91	
Injured persons						
Year	Number	Per 1,000 inhabitants	Per 100 accidents	Injured	Per 1,000 inhabitants	Per 100 accidents
2012	6	0.92	100.00	45 792	1.19	123.61
2013	10	1.53	111.11	44 059	1.15	122.91
2014	15	2.29	214.29	42 545	1.11	121.66
Killed persons						
Year	Number	Per 100,000 inhabitants	Per 100 accidents	Number	Per 100,000 inhabitants	Per 100 accidents
2012	0	0.00	0.00	3 571	9.28	9.64
2013	0	0.00	0.00	3 357	8.72	9.36
2014	0	0.00	0.00	3 202	8.32	9.16

2. METHODOLOGY

In this study, we utilized the risk factor analysis developed by Antov and colleagues [6,7]. With these authors' permission, the factors were modified and expanded to suit the purpose of this paper.

2.1. Analysis characteristics

All of the measurements were conducted in spring 2015, during regular work days, between the hours of 06:30 and 08:00 (morning traffic peak). The observations and measurements were not covert. Vehicle speed was measured for 20 randomly selected vehicles in the vicinity of four crossings. Speed was assessed as the time of travel between two stationary objects with a known distance in either direction; as this measurement method offers limited accuracy, in future studies, permission to use radar will be sought. The violation of traffic laws by the drivers was also recorded, such speeding, failure to yield to a pedestrian and illegal passing (note that in our factorial assessment, only speed played a role).

Each of the pedestrian crossings was observed for 15 minutes. The number of pedestrians violating traffic laws (such as running across the crossing, failure to observe the roadway before entering it and stopping on the crossing) was recorded.

2.2. Risk factors

The risk factors matrix was based on the following 26 factors, consisting of 23 engineering and environmental features, and three behavioural factors.

2.2.1. Engineering and environmental factors

Road width: Road width b, expressed in metres, measured across the street, between the kerbs (or between the shoulders).

$$m_1 = b$$

Number of traffic lanes: Number of traffic lanes p used by vehicular traffic, regardless of their width.

$$m_2 = \frac{p}{8} + 0{,}7$$

Presence of kerbs: The presence or absence of kerbs (or other physical separators) at the border between pedestrian and vehicular roadways.

$$m_3 = \begin{cases} 1.0 \text{ if kerbs present} \\ 1.1 \text{ if kerbs absent} \end{cases}$$

Bicycle path: The presence of a bicycle path, which has to be crossed, along the road, or a joint pedestrian-bicycle path. Due to the need to divide attention between two types of moving vehicle, this represents a factor that increases risk for pedestrians.

$$m_4 = \begin{cases} 1.1 \text{ if bicycle path present} \\ 1.0 \text{ without bicycle path} \end{cases}$$

Street lighting: The presence or absence of street lighting in the vicinity of the pedestrian crossing, excluding lighting dedicated to the crossing.

$$m_5 = \begin{cases} 1.0 \text{ lighting present} \\ 1.4 \text{ lighting absent} \end{cases}$$

Angle of crossing: The angle of the pedestrian crossing in relation to the road axis. Normally, the crossings should be at a 90° angle. Crossing at an angle generally increases risk, both due to limiting visibility and due to the increased travel path along the roadway.

$$m_6 = \begin{cases} 1.1 \text{ if } \angle \neq 90° \\ 1.0 \text{ if } \angle = 90° \end{cases}$$

Bus stop: In some cases, the crossings are designed so that pedestrians are forced to going through a bus stop pull-off area. This increases risk because of the occasional presence of stopping buses, which obstruct visibility, and the possibility of pedestrians hurrying to catch public transportation.

$$m_7 = \begin{cases} 1.1 \text{ for crossing in pull-off} \\ 1.0 \text{ for crossings not in pull-off} \end{cases}$$

Neighbouring crossings: Distance s, in metres, to the nearest intersection or traffic light-controlled crossing. The risk increases in the near vicinity of such crossings because of the lesser attention of drivers who may not expect another pedestrian crossing immediately after traffic lights**.**

$$m_8 = \begin{cases} 1.0 \text{ if } s \geq 150 \\ 1.1 \text{ if } 150 > s \geq 100 \\ 1.2 \text{ if } 100 > s \geq 50 \\ 1.3 \text{ if } s < 50 \end{cases}$$

Horizontal road markings: The quality and visibility of road markings in the vicinity of the pedestrian crossing. Horizontal road markings, as well as their quality and visibility, make a profound difference in terms of safety [8]. For the purpose of this analysis, retroreflectivity (of either the crossing markings or the approach lines) under dry or wet conditions, as well as skid resistance, was not measured. Instead, only a visual assessment was made, with losses of over 33% of the surface being worn or devoid of glass beads being considered as poor horizontal marking.

$$m_9 = \begin{cases} 1.0 \text{ with horizontal markings in good condition} \\ 1.1 \text{ with horizontal markings in poor condition} \end{cases}$$

Pedestrian visibility due to vertical markings: Pedestrians who wish to cross the road may be obscured by improperly positioned vertical signs. Even partial limitation of drivers' visibility is considered a negative factor.

$$m_{10} = \begin{cases} 1.0 \text{ with clear visibility} \\ 1.1 \text{ with obscured visibility} \end{cases}$$

Pedestrian visibility due to parked vehicles: In some cases, particularly in the areas where parking spaces are scarce, vehicles are parked too close to the pedestrian crossings. This significantly increases the risk because drivers and pedestrians cannot see each other. "Kerb extensions" are very effective in minimizing this risk.

$$m_{11} = \begin{cases} 1.0 \text{ with good visibility} \\ 1.1 \text{ with obscured visibility} \end{cases}$$

Road sign visibility: Pedestrian crossings must be marked, not only with horizontal zebra markings, but also vertical signs immediately prior to the crossing. Poor positioning of the signs may result in their being obscured by vegetation, buildings, advertisements, other road markings or improperly parked vehicles.

$$m_{12} = \begin{cases} 1.0 \text{ road markings clearly visible} \\ 1.1 \text{ road markings obscured} \end{cases}$$

Speed limit: The posted speed limit, *v*, in km/h, plays a profound role in safety (if the drivers obey it). As we are aware that the presented formula does not account for the increase in risk with increased speed, we are exploring options to account for the risk [2].

$$m_{13}=\frac{v}{60}+0{,}2$$

The presence of special pedestrian targets: Pedestrians frequently cross the street to reach special targets, such as schools, offices, workplaces, public transportation stops, public areas or shops. What is particularly characteristic of these targets is that they only operate at selected times; hence, their influence on safety is not constant.

$$m_{14}=\begin{cases} 1.0 \text{ no special pedestrian targets} \\ 1.1 \text{ special targets present} \end{cases}$$

Raised crossing: In case the crossing is raised to the height of the pedestrian pavement, a meaningful increase of safety can be realized, given that a raised crossing forces drivers to reduce speed.

$$m_{15}=\begin{cases} 0.6 \text{ pedestrian crossing raised} \\ 1.0 \text{ pedestrian crossing not raised} \end{cases}$$

Road humps: Road humps force drivers to reduce speed; thus, their location, immediately prior to a pedestrian crossing, can increase pedestrians' safety. Safety is considered to be increased if they are located on both approaches to the crossing; placing the hump in only one approach direction may not be effective.

$$m_{16}=\begin{cases} 0.7 \text{ road hump present} \\ 1.0 \text{ no road hump} \end{cases}$$

Coloured horizontal marking: Changing the surface colour is an attention-grabbing feature, which leads to safety increases. Most of the time, red is used as the background colour.

$$m_{17}=\begin{cases} 0.8 \text{ with coloured surface} \\ 1.0 \text{ without coloured surface} \end{cases}$$

Safety island or median: The presence of a permanent safety island or a road median is a meaningful safety feature. Pedestrians, despite having the right of way across the crossing, can cross a wide road in two stages, which lets them better assess the safety of the crossing manoeuvre and, in some cases, have a rest. In addition, traffic disruption is lower. Temporary safety islands (or other temporary installations dividing traffic directions) are considered to be less effective in comparison with permanent ones.

$$m_{18}=\begin{cases} 0.6 \text{ safety island or median present} \\ 0.8 \text{ temporary safety island present} \\ 1.0 \text{ no safety island} \end{cases}$$

Narrowing of the road: Narrowing the road at a pedestrian crossing ("kerb extension") is a meaningful safety feature. In a recent analysis, it was found to be highly effective in cities because it shortens the distance travelled by a pedestrian, eliminates the risk of parked vehicles obscuring the view, and generally leads to the lowering of speed [9].

$$\boldsymbol{m_{19}}=\begin{cases} \mathbf{0.7} \text{ with road narrowing} \\ \mathbf{1.0} \text{ no roadway narrowing} \end{cases}$$

Additional road signs: In some cases, additional vertical or horizontal road signs are included. Their purpose is to attract drivers' attention and warn them about the oncoming crossing; as such, safety is increased.

$$m_{20} = \begin{cases} 0.9 \text{ with additional marking} \\ 1.0 \text{ no additional marking} \end{cases}$$

Additional lighting: Street lighting dedicated to the pedestrian crossing, typically placed at the level of and above the crossing, is a meaningful safety feature at night. The risk is lowered, particularly if the roadway itself is not lit. As a possible drawback, we recognize the conditioning of drivers with regard to such a feature; it could be lowered if additional lighting was only turned when pedestrians are present.

$$m_{21} = \begin{cases} 0.8 \text{ additional lighting present} \\ 1.0 \text{ no additional lighting} \end{cases}$$

Barriers: Road barriers, separating vehicular traffic from pedestrians (and, in some cases, cyclists) in the direct vicinity of the marked pedestrian crossing, are a safety feature prohibiting pedestrians from careless crossing.

$$m_{22} = \begin{cases} 0.9 \text{ barriers present} \\ 1.0 \text{ no barriers} \end{cases}$$

Other factors: Factors not specified in the above analysis can be included here. Amongst them, one could list such road characteristics as the location of a crossing on a curve or a hill. Additional safety-enhancing features may also be included.

$$m_{23} = \begin{cases} 0.9 \text{ other safety features present} \\ 1.0 \text{ no other dangers present} \\ 1.1 \text{ other dangers present} \end{cases}$$

2.2.2. Behavioural factors decreasing safety

In addition to engineering factors, it is very important to assess the behaviour of both drivers and pedestrians.

Unsafe pedestrian behaviour: Pedestrians occasionally tend to break traffic laws and thus increase danger. Amongst the most common highly dangerous behaviours are running across the crossing, crossing on a red light or entering the roadway without checking for oncoming traffic. If over 20% of pedestrians break the traffic laws during the observation period, it is assumed that this particular population is increasing the risk.

$$m_{24} = \begin{cases} 1.0 \text{ if pedestrians tend to obey the traffic laws} \\ 1.2 \text{ if pedestrians tend to break traffic laws} \end{cases}$$

Actual speed of vehicles: The actual measured speed *v*, in km/h, immediately prior to the pedestrian crossing, plays a profound role in safety.

$$m_{25} = \frac{v}{60} + 0{,}2$$

Previous accidents: Accidents tend to occur in the same locations; hence, *x* is the number of accidents in which pedestrians were involved in the previous three years.

$$m_{26} = \frac{x}{10} + 1$$

2.2.3. Risk factor calculation

Risk factor $\boldsymbol{W}$ of the pedestrian crossing is the product of all of the above factors:

$$\boldsymbol{W} = \prod_{i=1}^{n} m_i$$

Based on these calculated risk factors, four levels, as shown in
Table **2**, were established [6]. While crossings with the factor $\boldsymbol{W}$ below '5' are considered safe (risk level '4'), at the opposite end of the scale are highly dangerous crossings (risk level '1', when $\boldsymbol{W}$ is above '15').

Table 2. Risk levels

Risk score W	W≥15	10<W≤15	5<W≤10	W≤5
Risk level	1	2	3	4
Risk description	Dangerous crossing	High risk	Moderate risk	Safe crossing

3. RESULTS AND DISCUSSION

Each of the evaluated 17 pedestrian crossings was assessed based on the 26 parameters described above. The safety risk is presented in Table 3 and charted in Fig. 3.

The infrastructure was found to be in average condition, with only a few outliers: both positive (additional signs and markings) and negative (absence of street lighting). The measured traffic speed exceeded the local speed limit of 40 or 50 km/h (the maximum measured was 76 km/h in a 40 km/h zone). This is believed to be caused by several factors, among which the following must be noted: (1) lack of driver discipline, (2) insufficient driver education, (3) poor enforcement, (4) geographic and municipal specificity, and (5) an inappropriately low speed limit in areas almost devoid of housing, which, in our opinion, conditions drivers to disobey the speed limits where they are needed. The differences between measurement points were low.

The majority of the crossings had low risk scores (second risk level). Based on the utilized method, they are generally safe. A low number of incidents and accidents confirm the assessment. However, one must note that three of the analysed points are at the upper border of the risk level, while even one negative occurrence, such as the worsening of the road markings, can increase vehicular speed or unsafe pedestrian behaviour, thus resulting in the classification of a high-risk area.

Table 3. Safety risk assessment of pedestrian crossings in Sułkowice.

Crossing no.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Engineering	7	4	8	6	6	7	4	7	7	7	5	9	7	7	7	7	9
Behavioural	1	1	2	2	1	1	1	2	1	1	1	1	2	1	1	2	1
Safety level W	**8**	**5**	**11**	**10**	**8**	**8**	**3**	**11**	**10**	**8**	**4**	**12**	**10**	**9**	**9**	**13**	**11**
Risk level	**3**	**4**	**2**	**3**	**3**	**3**	**4**	**2**	**3**	**3**	**4**	**2**	**3**	**3**	**3**	**2**	**2**

Only two crossings can be considered as safe, based on the utilized method, due to the presence of additional engineering features and very good marking conditions. Five crossings were found to be unsafe, mostly because of high speed and the lack of engineered traffic calming measures. The crossing labelled ‘12’ is of particular concern because it is located near a preschool and, somewhat surprisingly, located too far from any street lighting. Other crossings were scored in the low risk range, but it must be noted that, in the case of two of them, even one additional negative factor could result in a high-risk score.

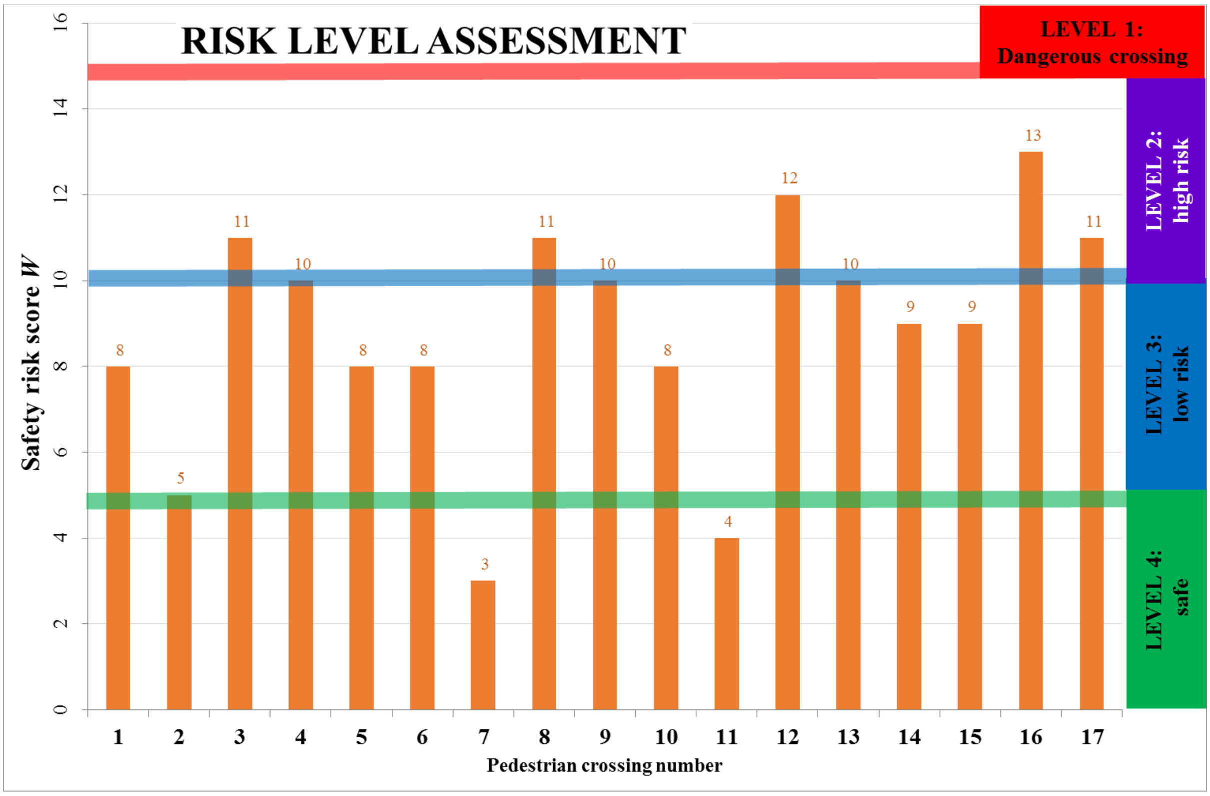

Fig. 3. Safety risk assessment of pedestrian crossings in Sułkowice; safety risk score *W*

The photographs shown in Fig. 4 and Fig. 5 demonstrate examples of safe and unsafe pedestrian crossings, respectively. The low-risk score (fourth safety level) of the crossing labelled ‘7’ (Fig. 4) can be attributed to additional horizontal and vertical markings. The use of a red background is likely to catch drivers’ attention and increase their vigilance [10]. Contrariwise, the crossing labelled ‘16’ (Fig. 5) has one of the highest risk scores; due to its poor design, it ends up at an island separating a bus stop from the road (thus, pedestrians are forced to break traffic laws). The absence of additional warnings increased the risk score.

In summary, the utilized method seems to meet expectations and permits the evaluation of the perceived risk at pedestrian crossings, based on both engineering and behavioural factors. Simultaneously, one must admit the weaknesses of the assessment procedure: namely, subjective parameters, particularly when evaluating pedestrian behaviour. The shortness of the observation periods definitely did not allow for all behavioural factors to be identified.

Fig. 4. A pedestrian crossing (labelled ‘7’ on the map in Fig. 2) is an example of a safe crossing due to enhanced horizontal and vertical markings

Fig. 5. A pedestrian crossing (labelled ‘16’ on the map in Fig. 2) is an example of an unsafe crossing, as it leads to a bus stop separation island, without any additional safety features

4. CONCLUSIONS

Improving safety at pedestrian crossings can be effectively accomplished by engineering work focused on calming vehicular traffic. In particular, raised crossings, road narrowing and safety islands were found to be highly effective [9]. Moreover, the use of additional horizontal markings is an inexpensive and efficient way to alert drivers of an oncoming dangerous section. Conversely, the removal of pedestrian crossings is definitely not advised as this would transform the road into a barrier, which in turn would decrease safety [11].

According to the assessment of 17 pedestrian crossings along a secondary two-lane road in the town of Sułkowice, two have the lowest risk scores and five have high-risk scores. Additional markings to warn drivers and the proper design of crossings are amongst the key safety parameters that decrease risk scores in this context, while the absence of engineered traffic-calming features, such as raised crossings, can significantly increase risk.

The methodology employed in this study, based on 26 factors, is, in the main, objective and can be utilized in any environment. The methodology is currently subject to more extended evaluation and modifications to include additional factors and adapt some of the weights in order to minimize subjectivity. Nevertheless, it must be remembered that every pedestrian crossing is unique, while safety is associated with both the infrastructure and the behaviour of all road users.

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