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Pedestrian Safety at Midblock Crossings on Dual Carriageway Roads in Polish Cities

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Abstract: Road crossings across two or more lanes in one direction are particularly dangerous due to limited sight distance and high vehicle speeds. To improve their safety, road authorities should provide safety treatments. These may include additional measures to reduce speed and narrow the road cross-section and the introduction of active pedestrian crossings. Equipped with flashing lights activated automatically when a pedestrian is detected, the crossings are painted red and have an anti-skid surface on approaches. The article presents an analysis of road user behaviour at pedestrian crossings on dual carriageways with a varying provision of road safety measures in some Polish cities. It also evaluates the effectiveness of the measures over time. The study was conducted before, immediately after and one year after the additional signage was introduced. The evaluation is based on how vehicle speeds changed before the pedestrian crossing, how pedestrians behaved versus the vehicle and their readiness to cross the street. The number of conflicts on selected crossings was also evaluated. The safety treatments under analysis were found to be less effective than the traditional pedestrian safety measures such as speed cushions or roads narrowed to one lane. This suggests that if used on dual carriageways the measures should only be temporary and should ultimately be replaced with traffic lights or a grade separated solution (a footbridge or tunnel) on exits from urban areas. No clear-cut conclusions about pedestrian safety can be drawn based on the traffic conflicts in question. The article is divided into the following sections: introduction with a review of the literature on pedestrian and driver behaviour studies at pedestrian crossings, including midblock crossings and dual carriageways; a description of the research method and test sites, the results, discussion of the results and conclusion.

Keywords: road safety; pedestrian crossing; pedestrian safety; dual carriageway

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Citation: Szagala, P.; Brzezinski, A.; Kiec, M.; Budzynski, M.; Wachnicka, J.; Pazdan, S. Pedestrian Safety at Midblock Crossings on Dual Carriageway Roads in Polish Cities. *Sustainability* **2022**, *14*, 5703. https://doi.org/10.3390/su14095703

Academic Editor: Marco Guerrieri

Received: 31 March 2022
Accepted: 5 May 2022
Published: 9 May 2022

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1. Introduction

Pedestrian safety is a key challenge when it comes to road safety improvements. More than one fifth of all road fatalities worldwide are pedestrians [1] with some countries recording even higher rates, exceeding one third [2].

Pedestrians are involved in more than 22% of road accidents in Poland and nearly 27% of all fatalities. More than 12% of all accidents happen on pedestrian crossings with nearly 9% of all road deaths occurring there [3]. Unsignalized road crossings across two or more lanes in one direction on dual carriageways are particularly dangerous due to limited sight distance and high vehicle speeds (Figure 1). In 2019 there were 452 accidents of this type in Poland with 458 people injured, of which 199 were serious injury accidents and 33 people were killed. While compared to 2014 accidents injuries and fatalities have fallen, serious injuries remain at a similar level (Figure 2). The risks are greater at non-junction pedestrian crossings [4]. Consequently, road authorities are working to improve road safety using safety treatments. These include crossings equipped with additional safety measures to reduce speed and narrow the road width and so-called active pedestrian crossings with flashing lights that are automatically activated when a pedestrian is detected. The crossings are painted red and have anti-skid surface on approaches.

Figure 1. Examples of pedestrian crossings on 2 × 2 and 2 × 3 cross-sections in Warsaw, with no additional treatment.

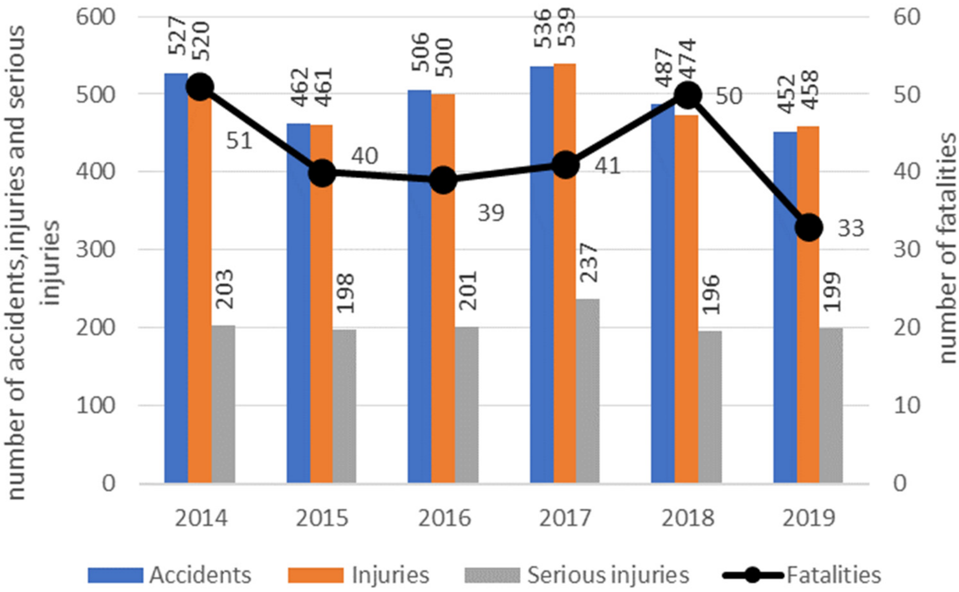

Figure 2. Accidents and accident victims at pedestrian crossings on dual carriageways between 2014 and 2019.

The objective of the article is to analyse the changing behaviour of road users at pedestrian crossings on dual carriageways with a varying degree of safety treatment

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provision and to evaluate the effectiveness of these measures over time using indirect road safety measures.

Research into the safety and conditions of pedestrian crossings is well documented in the literature. The analyses look at pedestrians crossing signalized crossings on a red light [5–7], the effects of red light duration on illegal pedestrian behaviour [8], the speed of pedestrians while crossing [9] and driver and pedestrian behaviour [10,11]. The studies cover unsignalized crossings primarily from the perspective of pedestrian [12,13] and driver behaviour [14,15] and their mutual relations at crossings [16,17]. Some of the studies look at pedestrian crossings at junctions [18,19], but there are many others which cover midblock crossings [20,21]. The analyses look at crossings near schools [22,23], and the safety of older pedestrians at crossings [24,25]. The studies compare traffic conditions [26] and safety [27,28] of crossings at junctions and in between them, and suggest that pedestrians at non-junction crossings are at a much higher risk [29–31]. These risks include primarily higher vehicle speeds on sections between junctions [32,33] and the fact that drivers are caught unawares when pedestrians cross the road away from a junction. In addition, if located there, pedestrian crossings interrupt the normal flow of traffic [34] and deteriorate the traffic conditions [35]. It is also very important to properly illuminate the pedestrian crossings [36].

Research into non-junction pedestrian crossings concentrates on the interaction between driver and pedestrian [37,38], using conflict analysis [21,39]. There are analyses of the distance between vehicles and the crossing at which pedestrians cross the road [40] and assessments of the effects of gaps between vehicles [41–44]. The work in [45] identifies the problems pedestrians face when assessing whether it is safe to use a midblock crossing.

Some of the work also studies how pedestrians cross the road away from the designated crossings (between junctions) to optimise crossing location [46–48].

Work in the field was supported by simulation tests designed to help analyse the effects of different scenarios on driver and pedestrian behaviour at non-junction pedestrian crossings [16,49,50].

Midblock pedestrian crossings across dual and single carriageways with more than one lane per carriageway require special attention. The effects of the types of cross-section on pedestrian behaviour are identified in the work [14]. Research shows that pedestrians are at a high risk at such crossings [51]. Other works point out that vehicle speed and vehicle clearance have the strongest impacts on such crossings [52,53]. Work has shown that the more lanes there are in one direction, the more conflicts there are between drivers and pedestrians [54,55].

Research into midblock crossings also concentrates on the effectiveness of pedestrian safety treatments [56]. Works show the positive influence of flashing warning signals and additional crossing lights on driver behaviour [57,58]. LED curb lights at crossings have proved effective along with flashing signals for drivers [59].

Research shows that some treatments at crossings only have a temporary effect [60]. The work demonstrated that a three-dimensional piano-keyboard-styled pedestrian crossing helped to reduce speeds on the crossing for three weeks only.

The literature review shows that there are not many research results available on the effectiveness of solutions to improve road safety at pedestrian crossings through more than one lane in one direction. This applies in particular to the research on the impact of the solution on the behaviour of drivers over a long period of time. The research presented by the authors partially fills this gap by presenting the effect of narrowing the lanes long after implementation.

2. Study Method

2.1. Test Sites and Data Collection

Empirical studies were carried out at pedestrian crossings on dual carriageways with a varying degree of safety treatment provision (no additional equipment, additional equipment but without change to lane geometry and with narrowed lanes). The objec-

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tive of the new traffic layouts was to improve road safety by reducing speed, increasing driver concentration on approaches to sites used by vulnerable road users and shorten braking distance.

The pedestrian crossings under analysis were equipped with additional road safety measures which included:

(a) so-called active pedestrian crossings (Figure 3a), consisting of flashing lights activated automatically when pedestrians are detected, zebra stripes against a red background and an extra coarse surface on approaches to the crossing;

(b) crossings with markings that narrow the lanes and road cross-section—i.e., a horizontal marking between same direction lanes and tilting vertical posts placed along the edges of the lanes (Figure 3b).

(**a**)

(**b**)

Figure 3. Example of pedestrian crossing treatments: (**a**) standard, (**b**)narrowed.

The work was carried out in Warsaw (active pedestrian crossings, 2 locations, ul. Popiełuszki—constructed September 2017 and ul. Grzybowka—constructed September 2017), Cracow (narrower cross-section, 2 locations in ul. Armii Krajowej—constructed June 2018) and in Gdańsk—constructed September 2019 (narrower crossing, 1 location, cross-sections without additional safety treatments, 2 locations as comparative cross-sections). The work in Warsaw, Cracow and Gdansk was conducted over three periods, i.e., more or less one month before the introduction of additional markings or narrowing ("before"), no more than one month after changes at the pedestrian crossing ("after 1") and about one year after the installation ("after 2"). The speed limit on all crossings is 50 km/h.

To analyse traffic on the test sites, video footage was obtained. Masts with cameras placed on them were used for video recording (Figure 4). Each of the crossings was videoed on weekdays using one or two cameras. Where two cameras were used, one recorded the footage from the pedestrian crossing and the other was installed for analysing traffic in both

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directions. Recorded videos were used to assess traffic volumes and speed in approaching pedestrian crossings, as well as to observe behaviour and the interaction between vehicles and pedestrians (observed conflicts).

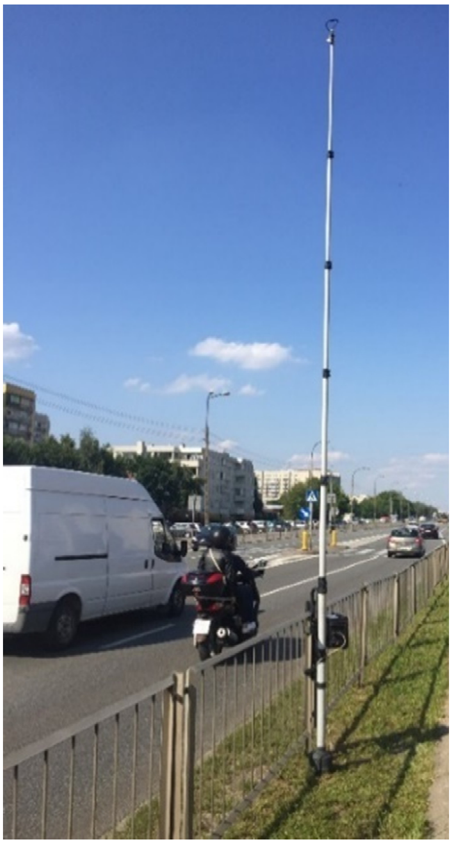

Figure 4. Example of a SCOUT camera installed at a test site.

To assess speed before the pedestrian crossing virtual cross-sections creating consecutive a measurement base (10 m length each) was included to each registered video. It helped to mark sections in known distance to each other. The first cross-sections were placed at a distance of about 10 m before the pedestrian crossing. Recorded videos were played 4 times slower to analyse video with higher accuracy. The moment when the vehicle arrived at each virtual cross-section was detected by pressing the dedicated keyboard button to fix the time. Speed was calculated as a quotient of measurement base and travel time which was calculated based on timestamps in which vehicle was detected in marked cross-sections.

The recordings were made from 5 (Krakow and Gdansk 10 a.m.–3 p.m.) to 24 h (Warsaw) for each period of analysis depending on the location to ensure that the samples were statistically significant.

The changes in road safety were evaluated indirectly based on differences in vehicle speeds before the pedestrian crossing, how pedestrians behaved versus the vehicle and the pedestrian's readiness to cross the street. The evaluation also included changes in the number of conflicts at pedestrian crossings on 2 × 2 or 2 × 3 (dual carriageway and two or three lanes in one direction) cross-sections in Gdansk, Cracow and Warsaw and, in the case of Cracow, on streets which included the modernised crossings.

2.2. Analysis of Empirical Studies

Empirical studies were conducted to estimate the following measures in the periods before and after the introduction of the new markings (short-term and long-term):

- traffic volumes: vehicles and vulnerable road users (hourly traffic volumes were used to analyse the conflict rate);

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- average vehicle speeds on analysed test sites about 10 m before the pedestrian crossing to identify how drivers perceive crossings;
- pedestrian behaviour before the crossing forming platoons, i.e., share of platoons and individuals using the crossing;
- interaction between pedestrians and vehicles, assessment based on conflict rate.

To analyse the pedestrian–driver interactions and identify dangerous situations, the method of traffic conflicts was applied. It is accepted that the conflict method goes back to the late 1970s and the definition of vehicle conflict was adopted in 1997. It reads: "A traffic conflict is a situation where two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remain unchanged". The method is applied to evaluating the effectiveness of road safety treatments ("before–after analyses").

Conflict situations are much more frequent than collisions or road accidents (5 to 10,000 times more often) which makes statistical analysis more versatile. In 1987 Hydén developed the safety pyramid [61] which shows the relation between road conflicts of different degrees of severity, conflict situations and undisturbed passages where:

- undisturbed passage means the movement of vehicles that are completely independent of one another;
- potential conflicts happen when users cross their paths of movements but do not change their behaviour (or only do it slightly);
- light conflicts happen when users cross their paths of movements and swerve to avoid a collision (but do not use brakes);
- serious conflicts happen when vehicles swerve and brake and the situation is very close to a collision.

It should be noted that the relations between the events will differ, depending on the particular element of road infrastructure. All of the observed conflict situations were assigned to four categories of conflict: potential conflict (road users cross their paths of movement, are close to one another but do not change their behaviour or do it only slightly), slight conflict (road users cross their paths of movement and swerve gently to avoid a collision—they slow, slowly come to a halt, change their path of movement), serious conflict (road users swerve rapidly, in the last minute and the situation is very close to a collision—they brake abruptly or turn), bypassing on the crossing (a vehicle bypassing another vehicle which stopped to let a pedestrian cross).

The analyses included the average serious conflict indicator [62] which is the average number of serious conflicts and bypassing on the crossing per one hour of observation at each of the analysed sites.

The road user observation period on all test sites before and after the treatments was the same. Because the analysed cross-sections are urban with a lot of stationary traffic over time, the effects of traffic volume on behaviour in the subsequent periods can be ignored. While traffic volume may impact site comparisons, it should not affect the effectiveness of road safety improvements over time. While a subjective assessment of the conflicts is biased to some extent, it does not have a significant impact on result credibility. To minimise bias, all objects were assessed in the same way using a fairly detailed definition of serious conflict [63].

3. Results and Discussion

The results of the tests were divided into three groups of vehicles, pedestrians and pedestrian–vehicle interactions. Tables 1–3 show the results for the period "before", "after 1" and "after 2". Examining the three periods was to show whether the assumed positive effect of the safety treatments was maintained over time.

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Table 1. Change of speed on analysed sites before and after.

City	Street	"Before"			"After 1"			"After 2"		
		Vm [km/h]	S [km/h]	S/Vm	Vm [km/h]	S [km/h]	S/Vm	Vm [km/h]	S [km/h]	S/Vm
Warsaw	Popiełuszki	50.3	14.5	0.29	43.5 *p*-value < 0.000 [2]	17.8	0.41	54.2 *p*-value < 0.000 [2] *p*-value < 0.000 [3]	15.3	0.28
Warsaw	Grzybowska	46.2	11.7	0.25	33.2 *p*-value < 0.000 [2]	15.4	0.46	29.3 *p*-value < 0.000 [2] *p*-value < 0.000 [3]	15.2	0.52
Kraków	Armii Krajowej 1	49.4	8.9	0.18	41.3 *p*-value < 0.000 [2]	8.4	0.20	44.1 *p*-value < 0.000 [2] *p*-value < 0.0035 [3]	7.5	0.17
Kraków	Armii Krajowej 2	50.6	9.5	0.19	41.6 *p*-value < 0.000 [2]	8.8	0.21	44.4 *p*-value < 0.000 [2] *p*-value < 0.0069 [3]	8.4	0.19
Gdansk	Obrońców Wybrzeża	33.2	17.6	0.53	27.8 *p*-value < 0.0054 [2]	15.7	0.56	29.5 *p*-value < 0.0493 [2] *p*-value < 0.336 [3]	15.5	0.53
Gdansk [1]	Hallera	49.4	28.1	0.57						
Gdansk [1]	Jana Pawła II	55.6	9.4	0.17						

[1] no safety treatments, [2] *p*-value (before—after 1 or 2), [3] *p*-value (after 1—after 2).

Table 2. Change of pedestrian behaviour on analysed sites before and after.

City	Street	"Before"		"After 1"		"After 2"	
		Separately [%]	Group [%]	Separately [%]	Group [%]	Separately [%]	Group [%]
Warsaw	Popiełuszki	80	20	80	20	80	20
Warsaw	Grzybowska	77	23	75	25	77	23
Cracow	Armii Krajowej 1	85	15	96	4	95	5
Cracow	Armii Krajowej 2	84	16	93	7	95	5
Gdansk	Obrońców Wybrzeża	75	25	92	8	90	10
Gdansk	Hallera	88	12				
Gdansk	Ul. Jana Pawła II	73	27				

Table 3. Change of conflict rate on analysed sites before and after.

City	Time	Street	"Before"	"After 1"	"After 2"
Warsaw	6.00–24.00	Popiełuszki	0.55	0.22	0.22
Warsaw	6.00–24.00	Grzybowska	0.83	0.78	0.67
Cracow	10.00–15.00	Armii Krajowej 1	1	0.25	0
Cracow	10.00–15.00	Armii Krajowej 2	0.8	0	0
Gdansk	11.00–16.00	Obrońców Wybrzeża	0.9	0	0

Table 1 presents a comparison of how mean speed Vm [km/h] in free flow (for vehicles with at least 6 s headway) changed and the standard deviation S [km/h] as a total for both lanes without distinguishing groups of vehicles. For each site the statistical significance of the before and after results was compared. To assess the statistically significant differences

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in speeds tests of significance for two means were conducted. The significance level of *p*-value for each of them was less than 0.05 which demonstrates the statistical significance of the differences in average vehicle speeds, excluding the site in Gdansk and mean speeds comparison between periods "after 1" and "after 2".

The changes in speed measured soon after the new marking or road narrowing show that average speed was reduced on all analysed sites between 5.4 km/h to 13 km/h. The resulting average drop in speed on five crossings is approx. 18%. About one year later the effect was not so clear-cut. While speeds were observed to fall, there was one increase compared to the "before" period. This suggests that other factors were also involved which may impact driver behaviour on approaches to the crossings or that the effect of change is diminishing. The average change in speed for all sites in the "after 2" period was approx. 13%. The speed variability rate (S/Vm) was much higher at the sites in Warsaw and Gdansk (0.28–0.53). The sites in Kraków showed a rate from 0.17 to 0.21 which suggests a more homogenous speed. This may be the result of other factors such as traffic lights nearby. The strong variation of the speed variability rate on the sites in Warsaw suggests that the speeds measured especially in the "after" period varied a lot, which may have a negative impact on road safety. The results from Gdansk sites confirm the average speeds recorded on 2 × 2 cross-sections with no additional safety treatments.

In addition, the lower speed at the Gdansk crossing before the road was narrowed may be related to the nearby signalised junction (approx. 120 m in one direction). However, this crossing shows a speed variability rate at 0.53 which is the highest for all the analysed crossings.

The results of the work are partly consistent with the literature which shows that new road markings designed to reduce speed may turn out to be unstable over time as a result of drivers becoming "accustomed" to the marking [60]. The study shows that 12 weeks after the special pedestrian crossing markings had been installed, the speed returned to the original level after an initial drop [60]. Other evaluations of the effectiveness of active pedestrian crossing markings in Wroclaw and Warsaw [64] as well as US [65,66] and Israeli studies [67] show that active signage systems are effective in reducing vehicle speeds and improving driver behaviour who are more likely to yield to pedestrians. However, not all the evaluations were conducted a year after the installation. This suggests that further work is required to include the long-term effects on road users over extended periods of time.

A sustainable improvement (lower vehicle speeds on approaches to pedestrian crossings) was successfully achieved on four of the five sites, including all sites with lane narrowing.

Pedestrian behaviour at pedestrian crossings was evaluated by analysing platooning and how it has changed. It was assumed that a higher share of individual pedestrians crossing the road for similar volumes of pedestrians and cars may suggest that pedestrians feel more confident and that indirectly their sense of safety has improved. Table 2 compares the percentage share of pedestrians crossing on their own or in groups.

Table 2 data show that the share of pedestrians crossing the street on their own increased by about 10 percentage points in the case of road narrowing. This may be because pedestrians perceive a crossing of two lanes as a "staged" crossing. As a result, fewer pedestrians form platoons. On Warsaw's sites the share of people crossing the street on their own and in a group did not practically change at all. This suggests that active pedestrian crossings do not change pedestrian behaviour but they do change the behaviour of drivers through the light signals.

The last comparison of behaviour looked at the pedestrian–driver interaction. The effectiveness was measured by the change in the average rate of serious conflicts and cases of bypassing on the crossing (number of conflicts in an hour). Table 3 compares the changes in the average rate of conflict. The average rate of conflict was calculated as:

$$\overline{CR} = \frac{10^3}{n} \sum_{i=1}^{n} \frac{Conf_i}{Q_{pi} \times Q_{Vi}},\ i = hour \quad (1)$$

where:

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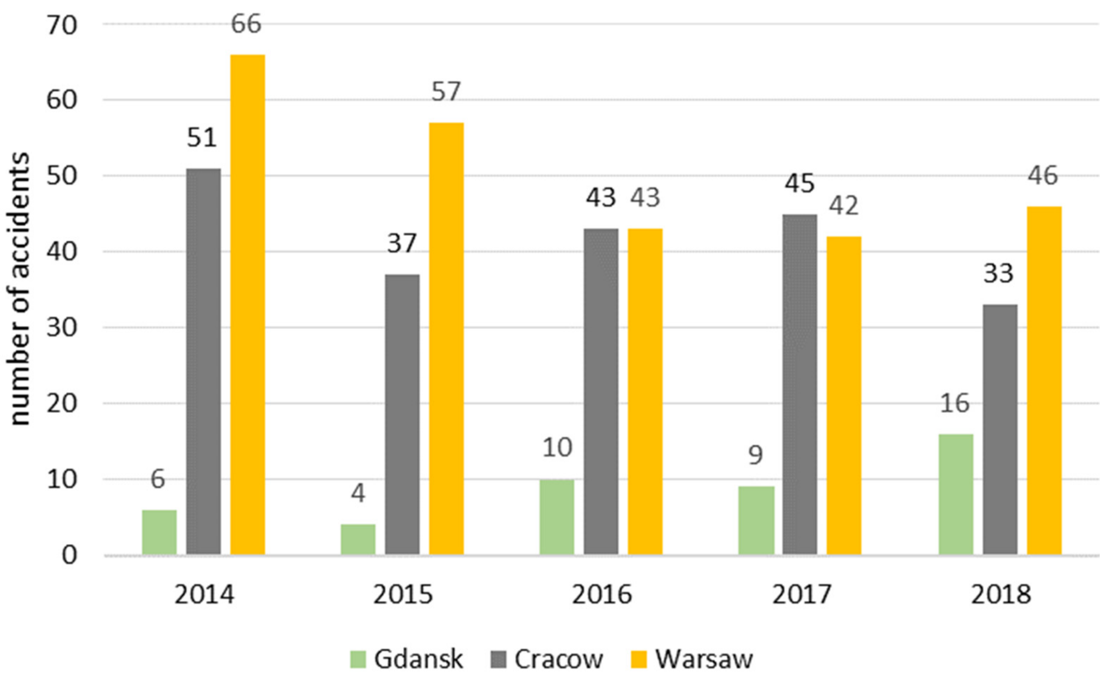
CR—conflict rate;
Conf—number of observed conflicts in hour *i*;
Q_p—pedestrian volume in hour *i*;
Q_v—vehicle volume in hour *i*.

CR was calculated in Krakow and Gdansk for 5 h and in Warsaw from 6 a.m. to 12 p.m.

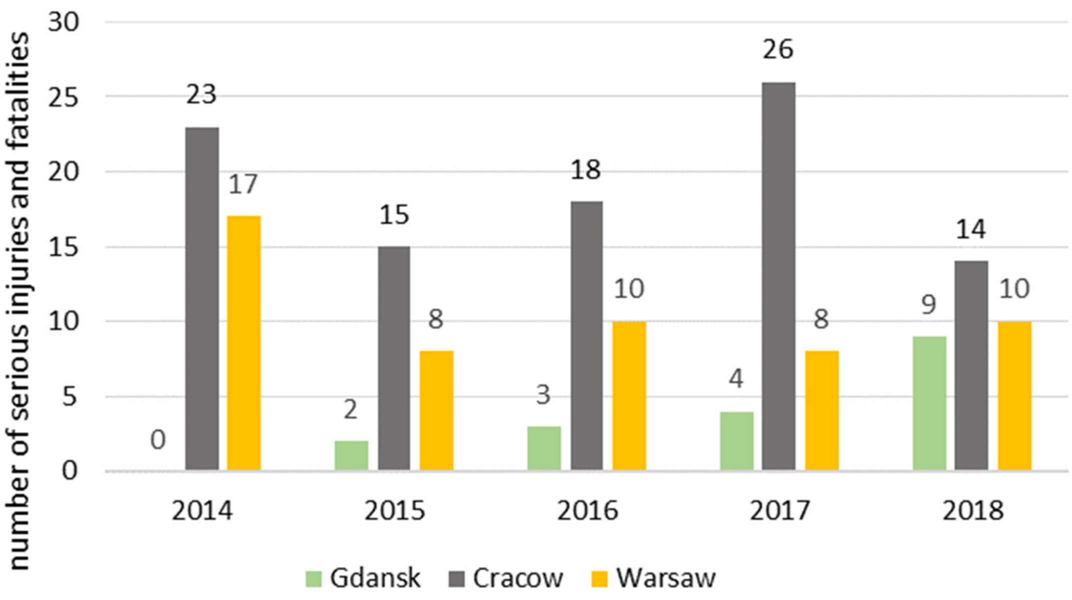
The results show that conflicts fell on all analysed sites. The reduction was higher in Cracow and in Gdansk which has to do with the presence of additional physical safety treatments. The results may also be impacted by the shorter observation time on those sites. However, it should be noted that the before and after observation times were identical.

Analysis of road conflicts two years before and after the changes on the sites in Cracow shows a 50% reduction in vehicles hitting a pedestrian on the analysed crossings (i.e., 2016—2019). Over the same time the city as a whole saw a 35% reduction in road accidents involving pedestrians hit by a vehicle on dual carriageway crossings. This shows that the treatments were effective (Figure 5).



(**a**)

Figure 5. *Cont.*



(**b**)

Figure 5. Accidents at dual carriageway crossings in Gdansk, Cracow and Warsaw: (**a**) number of accidents, (**b**) number of serious injuries and fatalities.

In Gdansk between 2014 and 2018 accidents went up significantly, serious accidents especially. In Warsaw in the analysed period, following a decrease until 2017, in 2018 there was an increase in this type of accidents and victims. The analyses suggest that systemic action is required to improve pedestrian safety on dual carriageways at pedestrian crossings. While signalised crossings are the most effective, alternative treatments should also be considered, including those analysed in this work.

4. Conclusions

The observations and the results show that pedestrian crossings on dual carriageways can be dangerous, with the main problems including driving over the speed limit, bypassing vehicles stopping before a pedestrian crossing or vehicles failing to stop before the crossing on both lanes. This calls for change and additional treatments at pedestrian crossings going across more than one lane in the same direction. When designing new 2 × 2 or 2 × 3 road sections, it is important to use signalization at pedestrian crossings or a grade separated pedestrian crossing (urban exit routes).

The article has presented a comparison of two low-cost safety treatments at pedestrian crossings, i.e., active crossings and narrower lanes using new layouts. The effectiveness evaluation of these safety treatments shows that improved safety is maintained over time generally, especially in the case of narrowed roads.

Warsaw's pedestrian safety treatments (new markings) proved less effective compared to the physical changes achieved as a result of narrowed lanes. As a result, if used on dual carriageways the treatments only produce a temporary effect and should ultimately be replaced with traffic lights or narrower cross-sections down to one lane in each direction. No clear-cut conclusions about pedestrian safety can be drawn based on the identified traffic conflicts.

The narrowing of cross-sections on the sites in Cracow and in Gdansk has helped to reduce speed by about 5 to 9 km/h immediately after the change of markings. One year after the installation of the new marking, the positive effects, i.e., lower speeds, can still be observed (4–6 km/h compared to before). The solution has also helped to reduce the number of conflicts. Pedestrian accidents two years after the changes fell in Cracow by about 50%. This shows that this treatment is more effective than the markings used in Warsaw.

It should be noted that the work was carried out on a limited number of test sites and primarily gives an indication of the nature of the changes and the effects of the safety treatments over time. The work, however, does not give a clear-cut assessment of the benefits of these measures if used in other locations.

Further work should consider a bigger number of test sites to formulate recommendations for additional safety treatments on dual carriageways. It is also important to identify the effects of other factors such as proximity to signalized junctions or the volume of pedestrian traffic.

Author Contributions: Conceptualization P.S., M.K., M.B. and A.B.; methodology, P.S., M.K., M.B. and J.W.; validation, M.K., M.B. and S.P.; formal analysis M.K. and M.B.; resources, J.W. and S.P.; data curation P.S., M.K. and M.B.; writing—original draft preparation P.S., A.B., M.K. and M.B.; writing—review and editing P.S., A.B., M.K., M.B., J.W. and S.P.; project administration M.K. and M.B. All authors have read and agreed to the published version of the manuscript.

Funding: The research related to Warsaw was funded by Warsaw Municipal Road Administration (ZDM).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the collection, analyses or interpretation of data, or in the decision to publish the results.

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