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Changes in Safety Performance on Single-Carriageway Roads After Installation of Additional Lighting at Pedestrian Crossing

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Abstract: Pedestrian safety is a critical concern worldwide, as pedestrians account for nearly a quarter of all road crash deaths. In Poland, in the last decade, the number of pedestrians killed in road accidents varied from 25 to 30% of all road accident victims each year. A similar tendency is observed in EU countries, but the average number of pedestrian fatalities is lower and amounts to 20%. Numerous activities have been undertaken to improve the safety of vulnerable road users. Land planning plays a crucial role in enhancing pedestrian safety. Effective land-use planning can mitigate risks by integrating pedestrian-friendly infrastructure into urban design. Numerous measures have been implemented to improve the safety of vulnerable road users, including education campaigns, speed reduction measures, and infrastructure enhancements. One of the latest initiatives involves enhancing the visibility of pedestrian crossings through the installation of additional lighting systems. In order to assess the effects of the undertaken activities, a number of zebra crossings with and without additional luminance were investigated. Crash data gained from police statistics, along with the calculated crash rates (CRs), were utilized to evaluate changes in safety performance at selected crosswalks. For this purpose, a „before–after" method was applied. Importantly, the research results did not show a clear impact of additional lighting on reducing the number of road crashes and they highlight that other factors, including the geometric characteristics of crossings and their location and proximity to land uses generating significant pedestrian traffic, significantly influence crash rates.

Keywords: pedestrian crossings; road safety; crash rate; additional lighting

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1. Introduction

During the last several decades, a number of pedestrian safety measures have been implemented worldwide, largely in developed countries. The European Union (EU) reduced the death rate by 39 percent from 2001 to 2010 and another 20% between 2010 and 2018 partly as a result of national policies, public education, and campaigns to make roads safer [1,2]. Road traffic crashes are caused by a combination of factors involving the road layout, vehicles, road users, and their interactions. Most accidents occur in urban areas, with roughly one in four pedestrian fatalities happening at or near pedestrian crossings. Consequently, about 8000 pedestrians are killed and many more are injured in road accidents in Europe each year. One in five road fatalities in the EU are pedestrians (Figure 1), a higher proportion than other vulnerable road users: 9% for cyclists, 3% for moped riders, and 15% for motorcyclists. Although the absolute number of pedestrian fatalities decreased by 20%, the overall reduction in road fatalities was 21%, maintaining the proportion of pedestrian fatalities within the total number of road fatalities. Within EU countries, the total number of road fatalities and pedestrian mortality are highest in the central and eastern EU Member States and Poland had the highest number of pedestrian fatalities in 2018.

That was the case despite the fact that this country had recorded the largest decrease in pedestrian fatalities at that time.

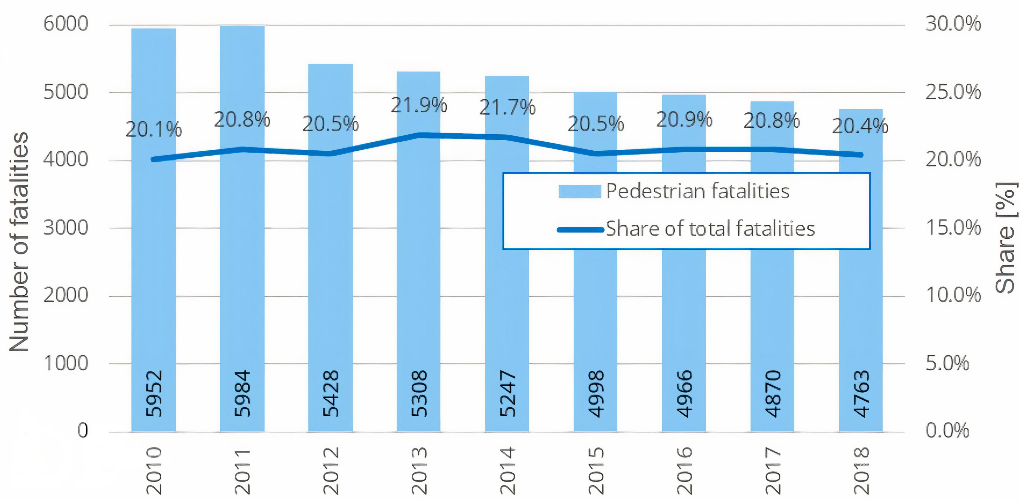


Figure 1. Number of pedestrian fatalities and their share in the total number of fatalities in the EU27 [3].

Pedestrian safety faces several critical issues, including high traffic speeds, driver behavior and pedestrian error, inadequate pedestrian infrastructure, and reduced visibility at night. These factors significantly increase the risk of pedestrian accidents and injuries. To address these concerns, urban areas often implement traffic calming measures to reduce vehicle speeds and create a safer environment for pedestrians [4–9]. The goal of these mainly physical measures is to reduce the excessive speed of vehicles, traffic volumes, and noise and exhaust emissions. Their effectiveness has been proven in many studies [10–14]. Regarding driver behavior, specific actions that increase crash risk have been addressed. Speeding and aggressive driving are major contributing factors to crashes. They extend the braking distance and increase the severity of collisions, especially in urban areas [15–18]. Behaviors such as tailgating, frequent lane changing, and ignoring traffic signals also increase the likelihood of collisions. Harrison and others [19–21] emphasized that alcohol and drugs impair drivers' cognitive and motor skills, leading to poor decision making and longer reaction times, which critically reduce the ability of drivers to avoid crashes. Knipling and Wang [22] also highlighted such issues in their research.

Regarding inadequate pedestrian infrastructure, numerous studies on pedestrian safety have identified issues such as inadequate crossing facilities, lack of pedestrian paths, and insufficient lighting at crossings as significant contributors to safety risks. Generally, recommended measures for decision makers included installing pedestrian crossings with clear markings, signalized crossings with countdown timers, refuge islands, and dedicated pedestrian zones [23].

Darkness reduces visibility for both drivers and pedestrians, increasing potential collisions [24,25]. Sullivan et al. [26] demonstrated a dramatic increase in the risk of pedestrian fatalities in darkness. Studies across Europe have revealed that nearly 20% of pedestrian crossings have poor night visibility [27]. Additionally, data from [2] indicate that nighttime accidents on zebra crossings represent 46% of the total, even though nighttime traffic flow constitutes only 20–35% of overall traffic. However, contrasting statistics were observed in the USA. According to [28], 74% of pedestrian fatalities occur in the dark, and pedestrian deaths make up only 15% of all traffic fatalities, compared to an average of 21% in the EU. Notably, some Eastern European countries have exceptionally high rates [29]. It is believed that proper street lighting may reduce or prevent road traffic crashes, injuries, and fatalities [30,31]. Investigations of vehicle speed in daylight and darkness conditions show ambiguous results, though. Assum et al. [32] found that in some cases, vehicle speed decreased in nighttime conditions, but in others, including zebra crossings, the instantaneous speed appeared to be even higher [33–35]. Additionally, vast investigations of different factors influencing travel speed in various road and environmental conditions conducted by Jägerbrand et al. [36] did not reveal any significant differences in speed attributable to light conditions.

Research studies investigating pedestrian safety improvements through additional lighting generally highlight the positive impact of enhanced visibility on reducing pedestrian-related accidents, particularly at zebra crossings. Many studies show that additional lighting can reduce the likelihood of crashes by increasing the visibility of pedestrians to drivers [37,38]. However, findings also suggest that lighting alone may not be sufficient and should be used in conjunction with other safety measures, such as road redesign and speed reduction, to create safer pedestrian environments. A study by Sullivan and Flannagan [26] examined the effects of increased illumination at crosswalks. They found that additional lighting substantially improved pedestrian visibility. They concluded that drivers were able to recognize and react to pedestrians at greater distances, which was associated with a decrease in nighttime accidents. Another study by Steinbach et al. [39] focused on urban settings and found that lighting improvements at crosswalks led to a measurable reduction in pedestrian injuries in these areas, further supporting the argument for lighting as a preventive measure. They also revealed that LED lighting had a stronger impact on improving pedestrian visibility than traditional sodium lights.

In contrast, some studies suggest that lighting alone may not fully address pedestrian safety issues. Other factors, such as crosswalk design and traffic speed, are also essentials. For instance, Bhagavathula et al. [40] emphasized that while additional lighting contributes to safer conditions, the effectiveness of lighting varies depending on crosswalk location, traffic volume, and road geometry. Studies by Ziolkowski [35] showed that additionally lit pedestrian crossings do not substantially influence drivers' speed and their speed did not differ significantly from that observed in the vicinity of zebra crossings without additional illumination. He also suggested that additionally illuminated pedestrian crossings should be supplemented with physical or video surveillance restrictions. Furthermore, Bullough et al. [41] investigated the influence of lighting on pedestrian behavior. They found that brighter crosswalks encouraged pedestrians to make safer crossing decisions, as they felt more confident and visible to drivers. However, they also observed that overly bright lights could create glare for drivers, especially in wet conditions, potentially offsetting some safety benefits. They suggested that while enhanced lighting is beneficial, careful design and placement are crucial to avoid unintended consequences.

A common method for investigating pedestrian safety in the United States is through surveys. Numerous analyses have examined the probability of accidents at pedestrian crossings in relation to road and crossing characteristics (width and marked or unmarked crossings; presence of traffic lights; and safety barriers) as well as driver speed [42,43]. Cui [44] applied statistical analysis to evaluate the age and gender distribution, light conditions, fatalities, and alcohol- or drug-use-related characteristics involved in midblock pedestrian crashes. They compared the safety of midblock crossings with that of intersections, concluding that there is a significantly lower potential for accidents if pedestrians cross at an intersection instead of a midblock location. Fayish et al. [45], in their study on the safety effectiveness of leading pedestrian intervals at signalized intersections, analyzed site characteristics, traffic volumes, and pedestrian volumes. Using a before–after study, they found that pedestrian safety can be significantly improved by implementing treated intersections, resulting in almost a 60% reduction in pedestrian–vehicle crashes. Naznin et al. [46] applied a similar methodology in their investigation of the pedestrian safety benefits of platform tram stops. Using a before–after crash analysis approach, their analysis showed an 81% reduction in pedestrian-involved injury crashes. A different approach was presented by [47,48], who employed observational studies and surveys to determine pedestrian behavior and the degree of familiarity of road users with traffic regulations regarding the priority of road users in various situations. Research in Israel examined pedestrian behavior while crossing roads, finding that most accidents occur on arterial multi-lane streets [49]. They noted no major deficiencies in the basic design elements of most sites and recommended a comprehensive approach to solving safety problems, including significant vehicle speed reduction in pedestrian areas. Studies by Hummel, conducted in the Netherlands, highlighted excessive vehicle speed as the biggest issue, especially concerning older people [50]. Tefft [4] and Wnavik [5] estimated the safety effect of road lighting on accidents in darkness in studies related to pedestrian injuries, impact speeds, and road lighting. Based on historical crash data covering a 30-year period, they concluded that the risk of injury accidents significantly increases in darkness. They revealed that, compared to daytime conditions, excessive driving speeds and reduced visibility at night are critical factors for pedestrian safety. They found that the risk of pedestrian accidents on lit rural roads increased by an average of 140% and on unlit roads by approximately 360%.

In Poland, between 2014 and 2016, pedestrian and bicyclist casualties made up over 40% of all fatalities, decreasing to 36% in 2020 [51]. Among these, pedestrians accounted for approximately 30% (Figure 2). Although pedestrians represent about 30% of all road fatalities, systematic studies on pedestrian behavior and vehicle–pedestrian interactions in Poland are still limited. Additionally, around 34% of all pedestrian-involved accidents occur at marked zebra crosswalks, where the number of recorded accidents remains high (Figure 3). This makes pedestrian crossing zones areas of elevated safety risk; hence, a necessity of improving the safety of vulnerable users has been repeatedly emphasized, and new pedestrian crossing design guidelines resulted from those findings [52–54]. Researchers are actively exploring ways to enhance the understanding of pedestrian–vehicle interactions to improve safety and efficiency on the roads. Szagala et al. [55] explored a new methodology for evaluating pedestrian–vehicle interactions by employing video analysis. They conducted investigations using digital footage at urban road crossings with various safety measures to validate the effectiveness of video image analysis in assessing pedestrian safety. Tomczuk et al. emphasized the importance of enhancing pedestrian visibility in crossing zones [56,57]. They examined luminance characteristics and lighting conditions, comparing various lighting solutions at pedestrian crossings. Their study focused on luminance, luminance contrast, and the effects of lighting on a pedestrian figure, identifying pedestrian visibility as a crucial safety factor. However, their research did not consider the overall impact on pedestrian safety. Budzynski et al. [58] investigated driver and pedestrian behaviors in pedestrian crossing areas. Based on pedestrian and vehicle speeds and a statistical analysis, they showed that vehicle speeds vary depending on the location—type of area, type of cross-section, section characteristics, and pedestrian crossing control—and on the presence or absence of traffic lights. In another study, Budzynski et al. [59] focused on identifying risks for pedestrians related to road infrastructure and roadside with different speed limits. Using police statistics, they indicated that limited sight distance, poor illumination, excessive speed, lack of speed management, and incorrect geometry (length of crossing and number of traffic lanes) are very hazardous. Zalesinska and Wandachowicz [60] used fuzzy logic algorithms to evaluate the quality of additional lighting. Szagala et al. [61] studied road user behavior at pedestrian crossings on dual carriageways, where active crossings and narrower lanes were implemented to enhance pedestrian safety. Using a before–after method, they assessed the effectiveness of these measures over time by conducting speed measurements before, immediately after, and one year after the introduction of additional signage. The results were inconclusive but generally indicated that safety improvements were sustained over time, particularly on narrowed roads. They also noted that effective speed reduction is a good measure for decreasing the number of pedestrian accidents.

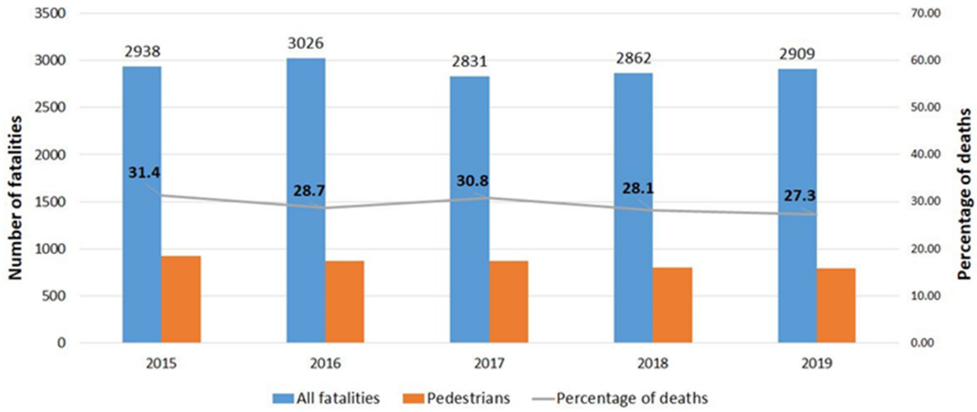


Figure 2. Number of pedestrian fatalities and their share in the total number of fatalities in Poland.

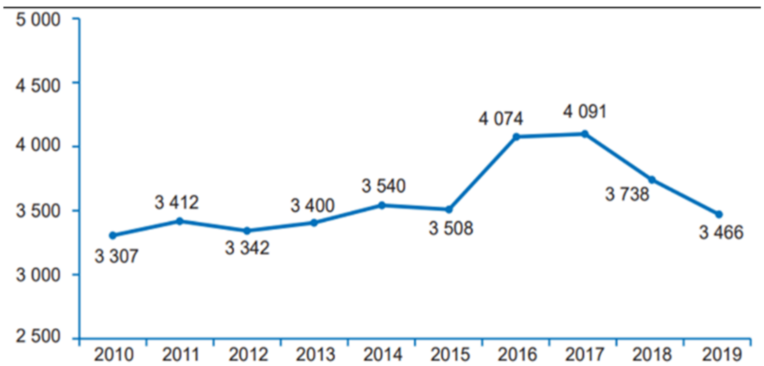


Figure 3. Number of accidents registered on pedestrian crossings in Poland.

The issues of improving pedestrian safety, despite the improving statistics in recent years, are associated with new implementations that are aimed at further improving their safety. The effectiveness of the implemented solutions remains an important issue and requires verification. One of latest innovations implemented in Poland on a large scale are pedestrian crossings with additional lighting, the effectiveness of which in terms of impact on improving safety has not been recognized. Hence, the main objective of this study is to evaluate the impact of additional lighting at pedestrian crossings on safety performance indicators for single-carriageway roads and roads with two or more lanes arranged within a one carriageway with no median strip, using a before–after study approach.

2. Research Site and Methodology

Improving visibility in the area of pedestrian crossings is related to planning, design, and maintenance activities and should be carried out in two main directions [62]:

- Improvement of visibility conditions;
- The use of measures to eliminate the threat to pedestrians in the absence of the required visibility area lists.

In the area of a pedestrian crossing, adequate visibility conditions must be ensured for pedestrians and oncoming drivers, both during the day and after dark. The area of good visibility is defined by the visibility distance L_{wz}/L_{wp} (Figure 4). Hence, the idea of additional lighting is to improve the visibility of pedestrians and pedestrian crossings in nighttime conditions. To meet these conditions a crosswalk with additional lighting system should be equipped with two extra lamps—one above the traffic lane according to the standards/guide issued in 2018 [62]. A Scheme of an exemplary location of the lighting system on a two-way single carriageway is given in Figure 5.

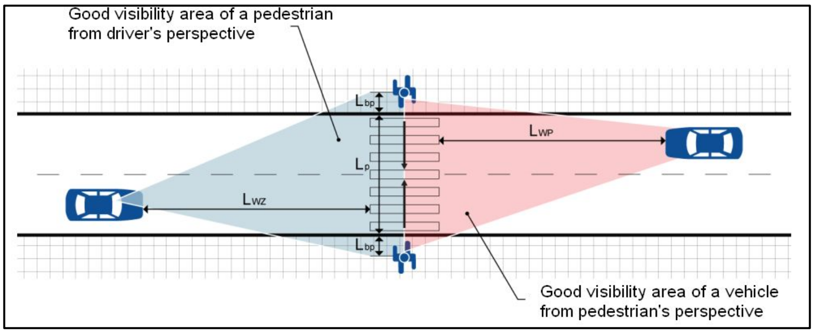


Figure 4. Areas of good visibility near a pedestrian crossing.

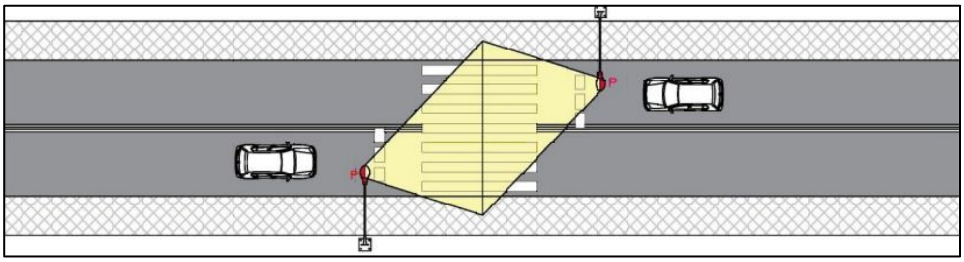


Figure 5. A scheme of a lighting location on a single carriageway.

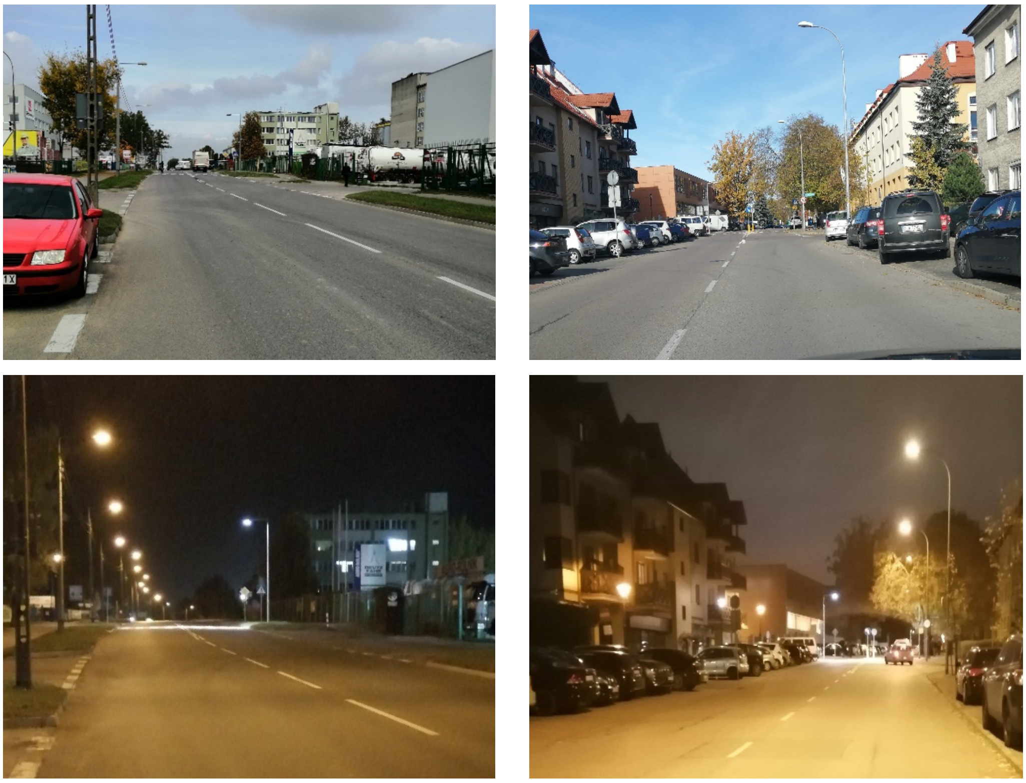
In Bialystok, a medium-sized city in Poland with a population of 300,000 inhabitants, a first pedestrian crossing with additional lighting system was built in 2011 as an innovative solution aiming at pedestrian safety improvement. By 2021, the system had expanded to include a total of 116 crosswalks.

For safety analysis, a minimum of two-year accident data analysis periods is recommended. For robust comparative safety analyses, it is advisable to use extended time periods that encompass road crash data from both before and after the intervention. A larger dataset of crash occurrences facilitates clearer observation of patterns and trends in changes over time. However, in pedestrian safety analyses, satisfying all sample size requirements can be challenging, often due to the restricted geographical scope and the relatively low incidence of pedestrian-involved accidents. To achieve an adequate sample size and enhance the dataset in the present study, the minimum threshold for the number of incidents required for a site to be included in the analysis was set at a relatively low level.

Considering aforementioned conditions, 8 out of 116 pedestrian crossings were chosen for detailed analysis. Data gained from police statistics covering registered road crashes over a five-year period (2014–2018) were analyzed for each pedestrian crossing. Since the lighting systems were installed in 2016, the two years before installation (2014–2015) were considered the "before" period and the two years after installation (2017–2018) were the "after" period. The installation year (2016) was treated as a transition year and excluded from further crash rate analysis. Finally, the analysis included crosswalks with at least two road crashes in the period prior to the installation of additional lighting. The relatively low threshold was chosen due to the limited number of zebra crossings and the fact that not every crossing experienced an accident during the analyzed period. All crossings were located on single-lane road sections, at intersection entrances (INT), and between intersections (MB). Details of selected crosswalks are presented in Table 1, while day and night views of chosen pedestrian crossings are presented in Figure 6. To evaluate safety performance changes, the number of crashes (including deaths, injuries, and damage only) and crash rates (CRs) calculated for varied crosswalk facilities were included in the analysis. The crash rate was selected due to its prevalence as a primary indicator in safety analyses, and it measures the number of road crashes per unit of measurement (a crosswalk). This allows for the assessment of the frequency of accidents in a given area and a comparison with other spots. In order to verify the significance of differences in the data at the analyzed intersections before and after the installation of additional lighting, a non-parametric Wilcoxon signed-rank test was applied.

Table 1. Characteristics of pedestrian crossings.

Pedestrian Crossing	Speed Limit [km/h]	Number of Additional Lamps	Travel Lane Width [m]	Refuge Island [m]	Location
PC_1	50	1	4.40	-	MB
PC_2	40	1	3.25	2.0	INT
PC_3	50	1	3.00	-	INT
PC_4	50	1	3.40	-	MB
PC_5	50	1	3.40	-	MB
PC_6	50	1	4.00	-	MB
PC_7	40	2	3.60	2.0	INT
PC_8	40	1	3.25	2.0	MB



(**a**) (**b**)

Figure 6. Examples of day and night views of analyzed pedestrian crossing: (**a**) PC_1 and (**b**) PC_6.

In every case, except for the pedestrian crossing PC_7, the crossings were equipped with only one additional lamp. For PC_7, presented in Figure 6, the installation was carried out in accordance with the standards, as illustrated in Figure 5.

3. Results and Discussion

The safety statistics showing road crashes registered in Bialystok in the analyzed period are presented in Table 2. They show the types of crashes and their consequences: number of injured and number of fatalities in the analyzed period.

Table 2. Police statistics of road crashes in Bialystok.

Type of Crash and Its Consequences	Year 2014	2015	2016	2017	2018
Accidents	55	62	69	73	71
Collisions	1938	2102	2300	2628	3010
Injured	58	69	81	81	78
Fatalities	5	2	1	2	5

Due to the very few accidents and fatalities recorded at the selected pedestrian crossings, in the following analyses, only crashes (the sum of accidents and collisions) were taken into consideration. Changes in the numbers of crashes at the investigated crosswalks are presented in Figure 7.

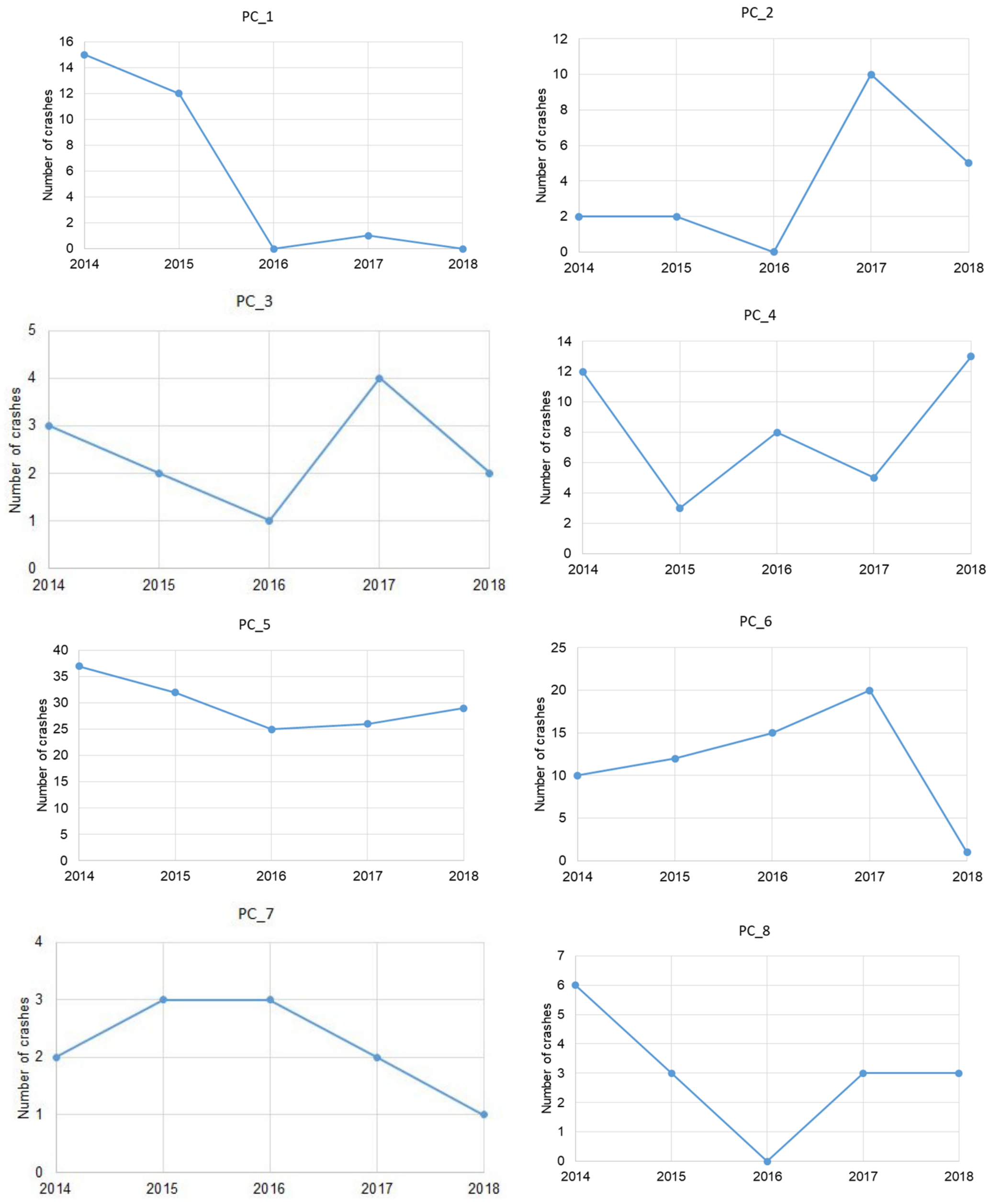
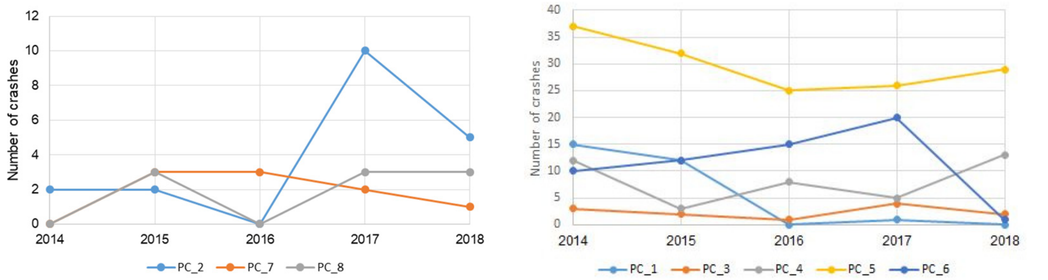


Figure 7. Changes in crash tendencies for the analyzed pedestrian crossings.

Analyzing the trend of changes in the number of crashes at pedestrian crossings, no clear pattern of changes can be seen. In some cases (PC_1, PC_3, PC_5, and PC_8), a decreasing tendency can be observed in the years prior to the installation of additional lighting, while in others (PC_6 and PC_7), the number of crashes increased. In order to determine possible dependencies of the change in the number of crashes in relation to geometry characteristics, pedestrian crossings were grouped into two categories. Data presenting trends in changes in the number of crashes in relation to the presence of a refuge island are given in Figure 8, while changes in the number of crashes in relation to the width of the travel lane are given in Figure 9.



(**a**) (**b**)

Figure 8. Changes in number of crashes at pedestrian crossings: (**a**) with a refuge island and speed limit 40 km/h and (**b**) without a refuge island and speed limit 50 km/h.

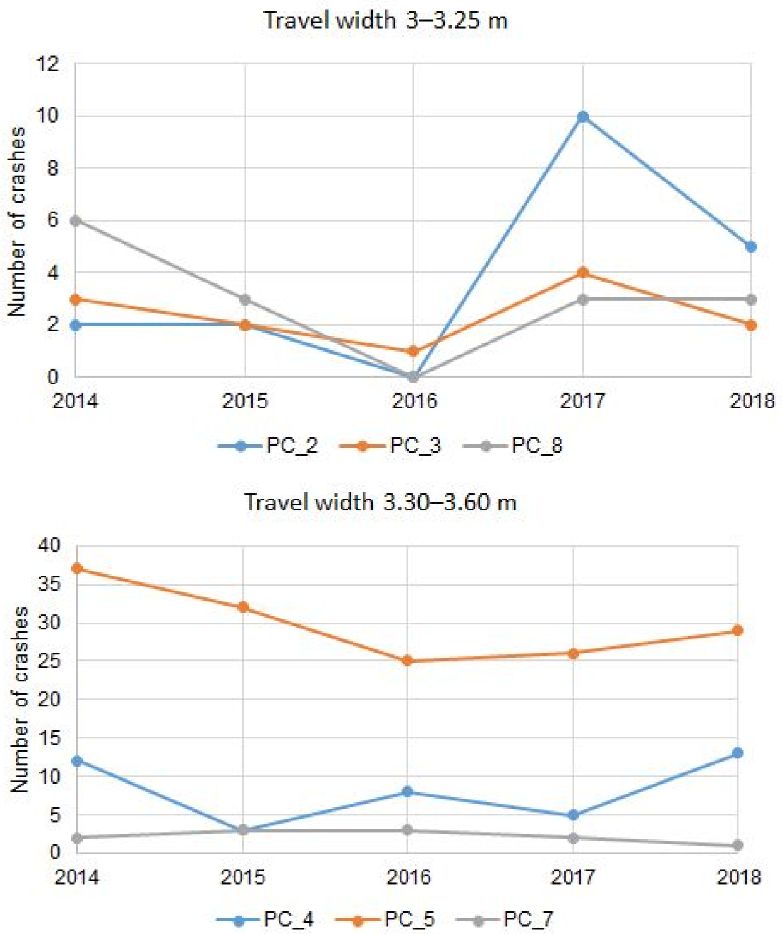


Figure 9. *Cont.*

Figure 9. Trends in changes in number of crashes at pedestrian crossings in relation to the travel lane width.

Figure 8a shows pedestrian crossings with a refuge island placed in the road with the local speed limit lowered to 40 km/h. Based on the presented data, it cannot be stated that the installation of additional lighting improved the safety conditions. Only in the case of crosswalk PC_7 did an increasing number of crashes before the installation turn into a clear decreasing trend. In the case of PC_8, before 2016, the annual number of crashes oscillated on a low level. Since 2017, the number of crashes has increased and stabilized on a relatively low level of three crashes per year after a drop to zero crashes in 2016. The effect of additional lighting somehow brought unexpected results in the case of PC_2. The low and stabilized number of registered crashes before 2016 was followed by a huge increase in the next year reaching 10 crashes, and that number fell further to 5 crashes in 2018. Analyzing crash data for pedestrian crossings without a refuge island (Figure 8b), there is not even one clear example showing a positive trend of decreasing numbers of crashes. In all cases, the data fluctuate, showing an increasing (PC_4 and PC_5) or a decreasing (PC_1, PC_3, and PC_6) tendency in the last two years of observations. However, in the case of PC_6, it can be said that the positive downward trend observed before 2016 was further strengthened in the period after the installation of additional lighting. Observing changes in crashes at PC_3 and PC_4, the number of crashes registered before and after the additional lighting installation remained very similar. An overall comparison of the safety situation at pedestrian crossings with and without a refuge island leads to the conclusion that lower speed limits and the presence of refuge islands create safer situations resulting in a lower number of crashes. The above considerations are supported by the statistical analysis using the Wilcoxon test. The results (Table 3) obtained from the analysis indicate no significant differences between the crash data from the analyzed "before" and "after" periods. Regardless of the criterion used for grouping the analyzed pedestrian crossings, no statistically significant change in the number of accidents was observed in any grouping system.

Table 3. Results of Wilcoxon test.

	T	Z	*p*
All crosswalks	29.000	1.1531	0.2488
With a refuge island V_{lim} = 40 km/h	1.500	1.6180	0.1056
Without a refuge island (V_{lim} = 50 km/h)	10.000	1.4808	0.1386
Lane width 3–3.25	2.500	0.9128	0.3613
Lane width 3.30–3.60	4.000	0.9438	0.3452
Lane width 4–4.40	1.000	1.4605	0.1441

The results obtained are inconclusive regarding the overall effect of implementing additional lighting. However, this ambiguity aligns with previous studies. The lack of clear positive effects from additional lighting installation, as confirmed by the Wilcoxon test results, is consistent with the results presented by Bhagavathula et al. [40,42], who emphasized that additional lighting alone might not sufficiently reduce pedestrian accidents. The researchers suggested that other factors, such as vehicle speed control, play a crucial role in enhancing pedestrian safety. Ziolkowski's work similarly found that lighting improvements alone do not guarantee a decrease in pedestrian crashes. This study stressed that a range of factors, such as road design and traffic calming measures, often contribute more meaningfully to pedestrian safety outcomes through more enhanced speed management. In addition, some findings by Sullivan and Flannagan [26] showed variability in outcomes depending on the specific context, indicating that lighting does not universally prevent accidents across all types of crossings or environments. On the other hand, a clearly positive influence of additional lighting on the reduction in number of pedestrians injured was reported by Steinbach et al. [39]. Among the cases analyzed, a similar trend of significant accident reduction was found for specific individual crossings (PC_1 and PC_7).

Trends in crash changes observed on the basis of data presented in Figure 9 are quite ambiguous. In the case of pedestrian crossings with the narrowest travel lane, the number of crashes was decreasing before additional lighting was installed. In the following years, the number of crashes first increased and then decreased again obtaining similar values to those registered before 2016. In the case of crosswalks located on streets with a travel lane width of 3.30–3.60 m, there was no clear pattern for the change in number of crashes before a new installation was applied. However, the following years brought a worsening of the situation and adverse effects. An increasing number of crashes can be observed at two out of three pedestrian crossings. In the case of pedestrian crossings situated on streets with the widest travel lanes, a very positive situation is observed at PC_1 where the number of crashes since 2016 was reduced essentially obtaining one and zero crashes in 2017 and 2018, respectively. In the case of pedestrian crossing PC_6, the number of crashes first increased in 2017 and then dropped to none in 2018.

For an in-depth assessment of the changes taking place at pedestrian crossings after additional lighting installations, crash rates (CRs) were determined. Crash rates refer to the frequency of traffic crashes occurring over a specific time period (here one a year) relative to a defined pedestrian crossing. The CR values were calculated separately for each year (Figure 10) and for the 2-year periods before and after the lighting installation (Table 4).

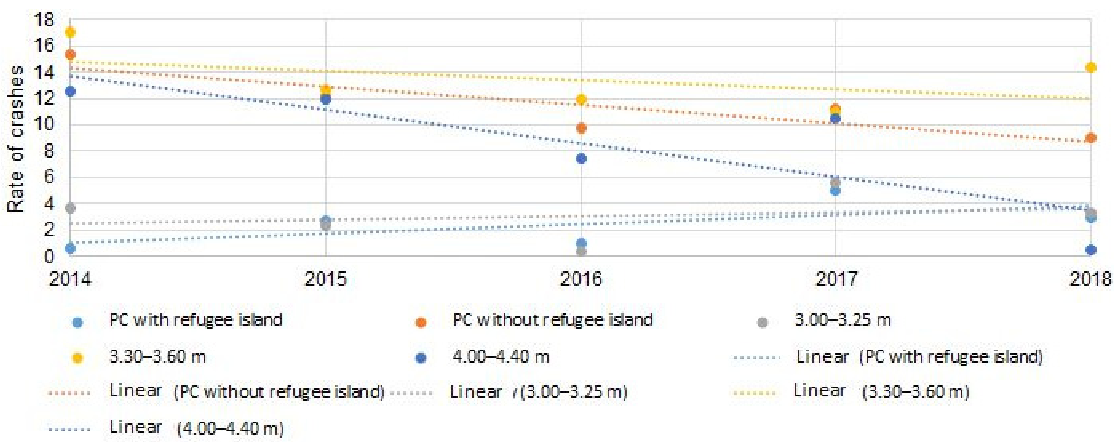


Figure 10. Trends in changes in number of crashes at pedestrian crossings in relation to the travel lane width.

Table 4. CR values for "before" and "after" periods.

	Rate of Crashes (RCs)	
	Before (2014–2015)	**After (2017–2018)**
For all pedestrian crossings	9.8	7.8
With refuge island	1.7	4.0
Without refuge island	13.8	10.1
Travel width 3.00–3.25	3.0	4.5
Travel width 3.30–3.60	9.9	8.4
Travel width 4.00–4.40	12.3	5.5
PCs at intersections	2.3	4.0
PCs in midblock	23.7	16.8

Linear trend lines presented in Figure 10 illustrate the changes in crash rates in subsequent years of the period under consideration. In two cases, there was an unfavorable trend indicating an increasing number of crashes recorded at the analyzed pedestrian crossings. In the remaining cases, the trend lines show that the number of crashes decreases over the period under consideration. It should be noted, however, that such a general observation based on trend lines could also be partially misleading. This can be seen in the case of crosswalks on roads with a lane width of 3.30–3.60, where the crash rate in 2018 increased by almost 30% compared to the previous year, while the trend line shows a reverse decreasing trend.

Considering crash rates calculated for the 2-year before–after periods given in Table 3, a positive result of safety improvement in the area of pedestrian crossings with additional lighting was obtained. Overall, a 20% decrease in the crash rates was achieved. The highest improvement was registered on crosswalks located on roads with a travel lane width of 4.00 and 4.40 m (55% decrease), whereas the smallest improvement was obtained on crosswalks where the travel lane width varied between 3.30 and 3.60 m (14% decrease). On the other hand, a closer look into the presented data reveals that in some cases, the safety statistics deteriorated after the additional lighting was installed. Unexpectedly, the situation worsened most at the crosswalks equipped with a refuge island for which the rate of crashes increased by almost 140%. It must be remembered though that this adverse effect may be due to a small number of investigated pedestrian crossings (only 3 crosswalks); in such a case, even one outlier can significantly distort the final result (high number of crashes registered in 2017 at PC_2 highly influences the calculated rate of crashes).

Previous studies have shown that driver speed highly influences traffic safety, and in urban areas, driver speed significantly depends on the geometry of pedestrian crossings and speed uniformity [35,63]. The studies have shown that speed uniformity deteriorated more at pedestrian crossings located on roads with a speed limit of 40 km/h than at crossings located on roads with 50 km/h speed limit, which in turn may contribute to an increase in safety risk.

Analyzing changes in crash rates in relation to the location of crosswalks, it must be said that considerably better effects were obtained in the case of facilities located midblock (29% decrease crash rate) compared to those situated at intersections (74% increase in crash rate). A high increase in statistics is, again, mostly due to the situation registered at PC_2.

The results obtained in areas of increased pedestrian traffic like school (PC_4) or church zones (PC_5) show that additional speed management measures should be applied to improve safety conditions. This could be simple to apply and also an effective speed reduction solution in the form of physical calming measure like speed cushions installed before the crosswalk or the redevelopment of an existing one into a raised pedestrian crossing [64,65]. A more innovative solution could be the installation of individual panels indicating travel speed alerting drivers exceeding speed or a combination of panels and traffic lights turning red in case of excessive speed [66–68] or the modernization of existing pedestrian crossings into active ones equipped with a flashing bean activated by the presence of a pedestrian.

4. Conclusions

This study analyses changes in safety performance indicators at pedestrian crossings where an additional lighting system was installed. A before–after method was applied to evaluate safety changes expressed by rate of crashes.

The conducted analysis included changes in safety rates related to varied factors such as location (intersections vs. midblock sections) and geometric characteristics of a pedestrian crossing (presence of a refuge island and width of travel lane). The obtained results are ambiguous in the effects achieved. A general positive influence of additional lighting systems was noted. As a result, the post-lighting crash rate (CR = 7.8) decreased by 20% compared to the pre-lighting period (CR = 9.8). However, more detailed analyses showed that the installation of additional lighting can also bring adverse effects and the results may be opposite to those expected. That was the case for crosswalks equipped with refuge islands located in areas with a locally reduced speed limit (V_{lim} = 40 km/h), where the CR values increased sharply after installing additional lighting. Nonetheless, a lowered speed limit and refuge islands still create more safety conditions, which is reflected by a distinctly lower number of crashes compared to the accident numbers at crosswalks located in areas with a default regulatory speed limit (V_{lim} = 50 km/h).

These findings highlight the importance of considering land-use planning and contextual factors when implementing pedestrian safety interventions. The following recommendations aim to guide local road authorities in effectively integrating pedestrian safety enhancements into broader urban planning and transportation strategies:

- Data-Driven Site Selection
    - The decision to install enhanced lighting should be informed by a thorough analysis of accident history, traffic volume, land-use patterns, and driver behavior at the proposed sites. Crossings near high-risk areas such as schools, hospitals, transit hubs, and commercial zones require priority in safety interventions.
- Integration with Urban Land Use
    - Crossings in high-density residential areas or near pedestrian-heavy land uses (e.g., parks, markets, or religious institutions) should consider additional measures beyond lighting. These may include speed limit reductions, traffic calming features, or active warning systems to complement lighting installations.
- Complementary Measures for Geometric Challenges
    - For crossings with complex geometric features (e.g., wide lanes or the absence of pedestrian refuges), additional interventions such as narrowing lanes, installing refuge islands, or implementing speed humps can amplify the safety benefits of lighting,
    - Where refuge islands already exist, a targeted analysis is required to ensure that lighting placement does not inadvertently increase risks due to altered driver or pedestrian behavior.
- Focus on Midblock Crossings
    - Midblock crossings, especially on roads with wide lanes (>3.25 m), often present higher risks due to the absence of natural speed-reducing features. Lighting enhancements at these crossings should be prioritized, with additional interventions as necessary to ensure safety improvements.
- Contextual Speed Management
    - The interplay between lighting and speed limits underscores the need for integrated speed management. In areas with low speed limits, lighting should be complemented by clear signage, enforcement measures, or physical speed-reducing features to ensure driver compliance.

This research has certain limitations, and further work is needed. The achieved results may be influenced by the limited number of crosswalks included in the analysis, making it possible for even one outlier to significantly distort the final outcome and potentially mask the actual trend. In future studies, the research scope should be broadened to encompass a greater number of illuminated pedestrian crossings, incorporate dual carriageways, and examine long-term changes in pedestrian safety at these crossings. Additionally, data on nighttime accidents should be isolated and analyzed separately. A comparison of nighttime and daytime accident data will provide a clearer assessment of the impact of additional lighting on crash rates and allow for more reliable statistical analysis.

An essential factor influencing the safety situation after the installation of additional lighting could be the that the guidelines for proper lighting (luminance, luminance contrast, and lighting intensity) were not published until 2018. Before that time, local road administrations had to act at their own discretion. This may have contributed to the existing additional lighting not meeting the appropriate criteria, and the visibility of the lighted crosswalks may have been insufficient. This also highlights the need for further extended research to be carried out in this scope.

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