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Modern Urban Transport Infrastructure Solutions to Improve the Safety of Children as Pedestrians and Cyclists

Maria Cieśla

Department of Transport Systems, Traffic Engineering and Logistics, Faculty of Transport and Aviation Engineering, Silesian University of Technology, 8 Krasinskiego St., 40-019 Katowice, Poland; maria.ciesla@polsl.pl

Abstract: This article presents the issues and needs for modern solutions in building urban infrastructure, based on the smart city idea to improve the living standards of residents. Particular attention is paid to one of the most important aspects of life, related to road safety of children as pedestrians and cyclists. Pedestrian sidewalks and bicycle paths with high pedestrian traffic are classified as dangerous areas in many countries. More than 3% of the injuries and fatalities among pedestrian road users that are victims of accidents occur due to crossing the road. Therefore, it is necessary to apply various technical infrastructure solutions to improve the safety of this group of inhabitants. The scientific purpose of this article is the assessment of the safety level of children in pedestrian and bicycle traffic and the analysis of road solutions supporting the maintenance of high-level city safety. The research was based on the analysis of statistical data of accidents and the diagnostic survey method determining the safety of the inhabitants of southern Poland. As a result, an analysis of the level of child safety in urban traffic was developed, as well as key factors affecting the levels of road safety, based on the opinions of respondents. Potential places with the greatest risk of collision with minors have also been identified. There are also proposals for infrastructure solutions aimed at minimising accident risk levels in designated areas.

Keywords: child pedestrian safety; child cyclist safety; infrastructure modern solutions; road safety

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1. Introduction

The enormous development of the automotive industry has been accompanied by many legal, technical, organisational and socio-economic problems. On the other hand, the increase in the number of passenger cars in cities is related to the increase in the number of road accidents, which has motivated many scientists and engineers to search for innovative solutions aimed at increasing the level of road safety.

The issue raised in this article is relevant and important for several reasons. First, it concerns the significant problem of road transport safety. According to a WHO report, approximately 1.35 million people die each year because of road traffic accidents. Road traffic injuries are the leading cause of death for children and young adults aged 5–29 years, and unsafe road infrastructure is listed as one of the key risk factors.

Secondly, the article refers to the real problem of preparing minors to participate safely in road traffic, which is the responsibility of adults and should be a social investment. The complexity of this issue is even more difficult as the physiognomy of children and adolescents is complicated. Children perceive traffic in a completely different way than adults, mainly due to a lack of ability to apply knowledge about road safety in practice or proper assessment of the behaviour of other road users, worse concentration and smaller height.

In general:

- 0–6-year-old children are not yet aware of the dangers that await them. For the most part, they cannot even judge whether a car is moving or not. They have big problems

with divisibility of attention. When they must focus on several things at once, they stop paying attention to traffic.

- 7–14-year-old children are better at road traffic and can realistically estimate the risk. As a result, they are less likely to create dangerous situations. In this age range, the perception of sounds is fully developed, and the field of view is also increasing. From the age of 11, they have a relatively good spatial orientation. Therefore, people under the age of 14 are much safer in road traffic than the previous group but still react slightly slower than adults.
- 15–18-year-old youth are the least endangered group of road users, but they create a lot of collisions in bicycle and motor traffic. They can assess traffic situations more realistically than the previous groups but often ignore dangers and try, for example, to run across the road in front of a moving car.

Due to the behaviour of individual groups, it is so important that parents and other adult road users pay special attention to children and, where possible, the use of infrastructure solutions to protect them.

Thirdly, the conducted research concerns modern infrastructure solutions supporting the visibility of short people and increasing their safety. Pedestrian sidewalks and bicycle paths with high pedestrian traffic are classified as dangerous areas and it is important to improve them.

The scientific purpose of this article is the analysis of the safety level of children in pedestrian and bicycle traffic in Poland and multi-criteria evaluation of road solutions supporting the maintenance of high-level city safety.

The paper is organised as follows. Section 2 includes a review of the literature on the aspects raised in the article. The problem is discussed with particular emphasis on child pedestrian and cyclist behaviour, especially at crossings, and the impact of it on safety. Section 3 describes the research approach and indicates the applied methods. Section 4 includes an essential part of the article related to the analysis of child safety on roads in Poland, conducted with statistical data analysis of road accidents and a survey of road users on the safety of children and young people. Section 5 presents road infrastructure improvements used for accident prevention. Three groups of infrastructural solutions are shown: increasing the safety of children at school crossings, improving visibility of pedestrian crossings and bicycle pathways and more advanced installations. Final part is devoted to the discussion of the results and conclusions.

The overall objective of the paper is to present the possibilities of using different solutions in road infrastructure for improving people's road safety indicators.

2. Literature Review

In order to carry out research analysis related to the purpose of the article, at the beginning, it is necessary to explain the basic issues of road safety and the behaviour of its participants. Road users can be categorised as car, van, lorry, bus and other vehicle drivers, motorcyclists, pedestrians and cyclists. The article focuses on a special group of cyclists and pedestrians (children and underage youths), for whom adult guardians are responsible.

Many studies concern the precise behaviour of pedestrians in road traffic, which, as noted in [1], always concerns the dilemma between safety and convenience. Irrational decisions regarding the behaviour of people on the border of risk are presented in [2], indicating that time saving was the main reason for incorrect behaviour. In [3], researchers showed that most pedestrians cross the road during their first attempt and use the shortest path to cross, even if it is a high-speed, six-lane, divided arterial road that runs through a high-density urban area.

Additionally, in the analysed age group, the importance of using city bikes in an urban area [4,5] was taken into consideration as well as additional risk factors that need to be addressed [6,7].

The study in [8] tried to understand the preferences of pedestrians towards using different types of road crossing facilities, in terms of pedestrian willingness to walk to access

them. The preference for a particular facility (e.g., straight or staggered signalised crossing, footbridge, underpass) sometimes depends on non-obvious and individual factors, such as habit [9], aesthetics, hygiene aspects [10] and others. Age, gender, physical disabilities [11], whether they were carrying baggage and luggage, as well as their crossing patterns, were examined on pedestrian flow characteristics such as crossing speed and waiting time [12,13]. As claimed in [14], the problems always involve interpenetrating vehicular and pedestrian streams, the consequences of which include variable parameters of vehicle queues emerging in pedestrian crossing-affected areas, delay, difficulties crossing the road by pedestrians, etc.

The review of the literature on pedestrian crossing and cyclist behaviour shows a wide variety of methods, including self-completed questionnaires [15], personal interviews [16], experiments [17], pedestrian tracking [18], GIS analysis [19], simulations [20], video-based stated preference surveys [21], videotaped observations [22,23] and revealed preference analysis [24]. Most studies found that long waiting times and elements that decrease safety, accessibility and personal security influence road crossing behaviour, route choice and the propensity to walk. The resulting values of movement speed can be useful during the spatio-temporal analysis carried out by forensic experts into the opinions on road accidents occurring, involving underage pedestrians [25].

Another group of studies are concentrated on the construction of pedestrian crossings. The authors of [26] indicated that there is strong evidence for the positive effect of road measures (traffic lights [27], roundabouts [28–30] and refuge islands), especially on the number of pedestrian-related accidents. Crossings equipped with flashing yellow lights, refuge islands and traffic lights required much more appropriate behaviour from car drivers. The analysis results in [31,32] showed that using pedestrian countdown timers during the Red Man phase led to more violations and running behaviour in children. Risk-taking behaviours listed in [33] related to crossing by riding, with a high probability of crossing on red and of not checking traffic prior to crossing at an un-signalised crosswalk, which was higher for children riding an electric bicycle or kick-scooter.

Numerous analyses of the safety condition [34] confirmed that infrastructure elements support children crossing at a crosswalk, the behaviours of which are even more dangerous when walking without the interference of the observers [35]. The unsafe behaviours observed are usually: not stopping at the curb, not looking before crossing, attempting to cross when a car is nearing and running across the road. According to [36], boys may be at greater risk than girls, at least for some age groups. Research in [37] was aimed at studying the effect of roadside distractions (noise, cell phones [38]) on pedestrian road crossing behaviour, focusing on elementary school-aged children, who are less capable of making a safe road crossing decision and are more vulnerable to the effect of distractions. Taking these results into account, additional infrastructure elements for pedestrian crossings (such as protective barriers) may help to avoid a dangerous situation.

What is more surprising, according to research, is that children accompanied by an adult committed even more unsafe practices. From these children, more unsafe behaviours were committed amongst those not holding hands with the adult [39]. In [40], researchers proved that children's acts are influenced by adults and children rely on their parents.

Previous research on the topic allows us to draw conclusions that children's crossing behaviour should be considered when people plan and design the crossing facilities that children may use. The risk-taking attitude of young road users should be considered in the development of injury prevention programmes focusing on child and parent education and training, and by adapting the infrastructure of urban environments to better meet their needs.

3. Materials and Methods

The research was conducted in four stages. The initial stage concentrated on the literature and documents (legal acts, educational programmes) review. As a result, the

assumptions and objectives of road safety were developed. Additionally, the basic areas of problems related to this research area and applied improvement methods were defined.

The next stage was focused on the statistical data analysis among children as pedestrians and cyclists' safety in Poland, with an emphasis on the causes of accidents resulting from road hazards. This section uses official statistical data, mainly from police data for 2019, considering such information as: the time and place of road accidents, their types, causes, perpetrators and victims of accidents and, in particular, the issues of the safety of pedestrians and other vulnerable traffic participants. Part of the data was also obtained from a special database that maintains the system of recording accidents and collisions in Poland. The search engine is a non-commercial website that allows the search for collisions and road accidents in Poland, and its database uses the data of the Accident and Collision Record System provided by the Police Headquarters in Warsaw. The analysis focused only on road accidents, which, as in other European countries, are classified as incidents involving people.

Subsequently, a diagnostic survey method was conducted, to determine the opinions of all road users on the safety of children and adolescents on the road and examine the level of satisfaction of respondents with pavements and bicycle routes in southern Poland. It was based on 7 questions with 217 respondents.

The final stage was based on survey results, which made it possible to indicate various infrastructure solutions used to increase the safety of road users, with particular emphasis on children. Further conclusions related to usability of the solutions to improve the safety of children as pedestrians and cyclists among modern urban transport infrastructure were drawn. Additionally, a multi-criteria assessment of infrastructural solutions increasing children's road safety leading to the ranking of the improvements was prepared.

4. Safety of Children as Pedestrians and Cyclists in Poland

The analysis of child safety on roads in Poland was conducted with statistical data analysis of road accidents for the collection of quantitative data. Additionally, a survey on the opinions of road users on the safety of children and young people on the road was prepared, to complete the research with qualitative data.

4.1. Road Accident Statistics Analysis

Every day in the European Union, an average of thirty children (0–14 years old) are seriously injured, and every other day, three die in road accidents. During the decade 2009–2018, nearly 7000 children died because of injuries sustained in road accidents across the EU.

The safety of children in road traffic has significantly improved in almost all countries of the European Union. This does not change the fact that, in 2018, about 530 children were killed on EU roads [41], and nearly 92,200 were injured, of which about 11,200 were seriously injured. Between 2009 and 2018, the number of child deaths from road accidents decreased by 44% in the EU, while at the same time, the number of fatalities for the rest of the population decreased by only 28%. In Poland, the decline was 56% for child fatalities and 37% for the rest of society, respectively. Thus, Poland recorded a faster improvement in the safety of the youngest road users than many EU countries.

In the decade 2010–2019, there were nearly 350,000 road accidents in Poland, almost 15% of which were accidents involving children and adolescents: 32,800 people died in these accidents, including nearly 1600 children and adolescents, i.e., this group accounted for 5% of all deaths. While the total number of fatalities decreased by 26% between 2010 and 2019 (see Figure 1), this decline reached 50% for children and adolescents. The share of the number of child deaths in road accidents decreased from 6% of the total in 2010 to 4% in 2019. The analysis of data on accident victims shows that the age structure of fatalities has changed over the past decade. In 2010, children aged 0–14 accounted for 48% of those road users killed in the age group 0–17, and the remaining 52% were victims among adolescents

aged 15–17. However, in 2019, these proportions changed and amounted to 58% of deaths among children and 42% of deaths among adolescents.

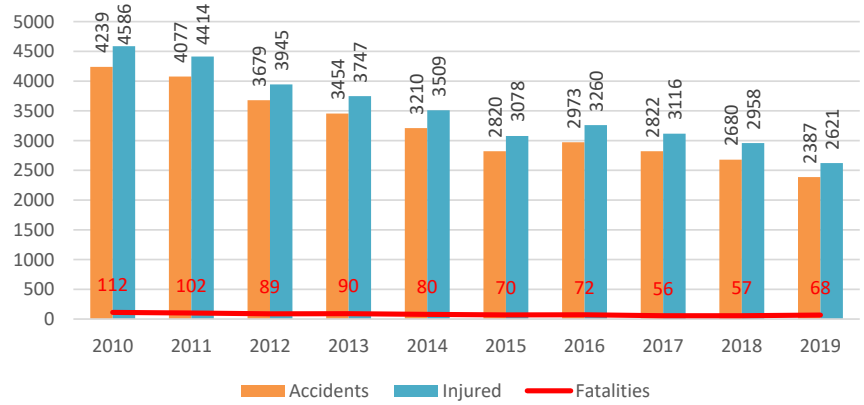


Figure 1. Road accidents involving children aged 0–14 in 2010–2019 in Poland.

In 2019, 6077 accidents with 64% of fatalities occurred in urban areas, and 644 accidents with 36% fatalities occurred in undeveloped areas of Poland. Further statistical analysis on the safety of children was carried out without the division into the road environment of the accident.

The number of accidents in the southern part of Poland that took place in 2019, mainly in the Silesian Voivodeship, was very high and amounted to 9.8% of over 30,000 accidents. The death rate per 100 accidents was 6.7, which was quite low compared to other regions. The indicator of the number of injured per 100 accidents was 120.1, the second highest in Poland, after the Mazovian Voivodeship.

The analysis of data on road accidents in Poland shows that children (0–14 years old) and adolescents (15–17 years old) are the least endangered groups of road users.

The growing independence of children, resulting from their development, means that, as they grow up, this risk increases significantly, and they become more and more exposed to participation in road accidents.

The greatest number of accidents involving children and adolescents takes place:

- In the summer months, especially in June, see Figure 2.
- In the morning and early afternoon on the way to and from school.
- On Fridays, in terms of the number of accidents, while on Saturdays and Wednesdays, the highest number of deaths among children were recorded, see Figure 3.

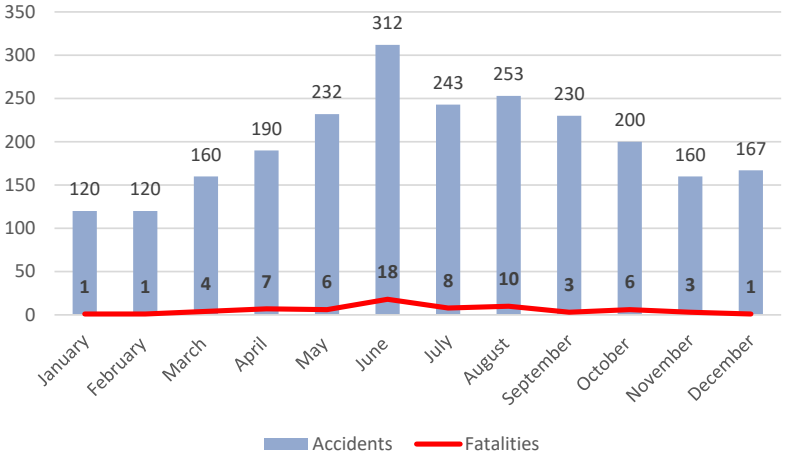


Figure 2. Road accidents involving children aged 0–14 in 2019 in Poland.

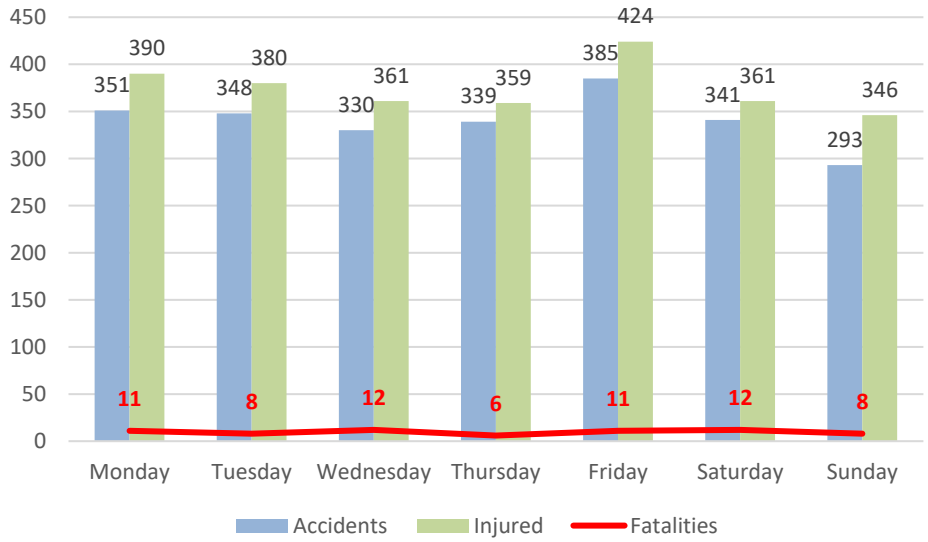


Figure 3. Road accidents involving children aged 0–14 by days of the week in 2019 in Poland.

The vast majority of all victims among children aged 0–6 were vehicle passengers (as much as 80.7%), including 81.8% of fatalities. This trend is very worrying because it proves that the youngest are exposed to the risk of losing their life or health primarily due to the mistakes of adults. In the case of children from the older 7–14 age group, the most fatalities were among the drivers and the injured among the passengers. As shown in Figure 4, for the older age group, the level of accidents involving drivers, most often bicycles, increases.

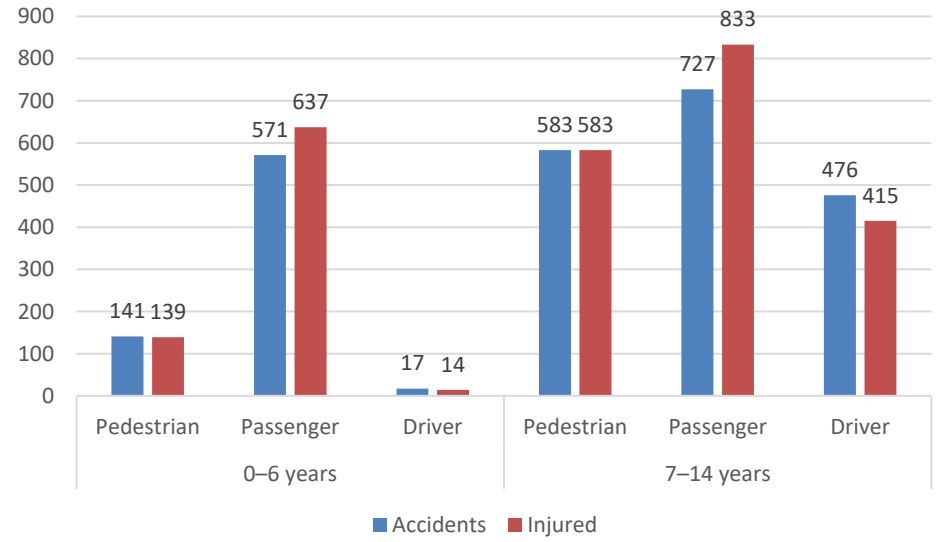


Figure 4. Road accidents by age group and role in 2019 in Poland.

The greatest number of killed and injured children and adolescents is in the group of car passengers, followed by pedestrians, see Table 1. Based on the data [42] for 2019, 7005 accidents involved pedestrians. Unfortunately, 16% occurred in the 0–17 age group. Victims constituted 3% and the injured 17.3% of all incidents concerning the analysed age group. Among 1626 accidents involving cyclists in the analysed age group, there were 21.5% of events, including 9% fatalities and 22.2% children injured.

Table 1. Road accidents with children as pedestrians and cyclists in 2019 in Poland.

Group	Pedestrians			Cyclists		
	Accidents	Fatalities	Injured	Accidents	Fatalities	Injured
0–6 years	143	4	139	10	0	11
7–14 years	594	11	583	244	7	241
15–17 years	383	9	374	96	5	93
Total	1120	24	1096	350	12	345

Among the factors that have a decisive influence on road safety, in first place is the person. It is the behaviour of particular groups of road users that generally influences the occurrence of road accidents. Other factors, including infrastructural ones, were much less important. In 2019, most accidents in Poland were caused by the fault of:

- Drivers (87.6%), due to: failure to give way at a right of way (27.3%), failure to adjust speed to traffic conditions (23.6%), failure to give way to pedestrians at a pedestrian crossing (11.0%), failure to give way to pedestrians in other circumstances (1.5%), incorrect crossing of bicycles (1.0%), failure to give way to a pedestrian when turning into a crossroad (0.8%) and overtaking a vehicle before a pedestrian crossing (0.2%). Of all drivers, 6.1% were cyclists.
- Pedestrians (6.2%), mainly due to: entering the road directly in front of a moving vehicle (50.1%), crossing the road in a prohibited place (11.6%), entering the road from behind a vehicle, obstacles (10.7%) and entering the road at a red road light (8.2%).
- Passengers (0.4%).
- Complicity (1.0%).
- Other causes (4.8%), for example related to the technical malfunction of the vehicle (lack of tyres, lighting, faults in the braking or steering system), objects and animals on the road and related to the poor condition of the road or traffic organisation.

Although most of the accidents occurred in urban areas in 2019, more people died because of accidents in non-built-up areas (one in five accidents, and one in eighteen in built-up areas). It is very important to analyse the place where the accidents occur (Figure 5) since it may be a potential place of necessity to modernise the road infrastructure. Most accidents (73.8%) take place on the road, but many also belong to other infrastructure places of public use.

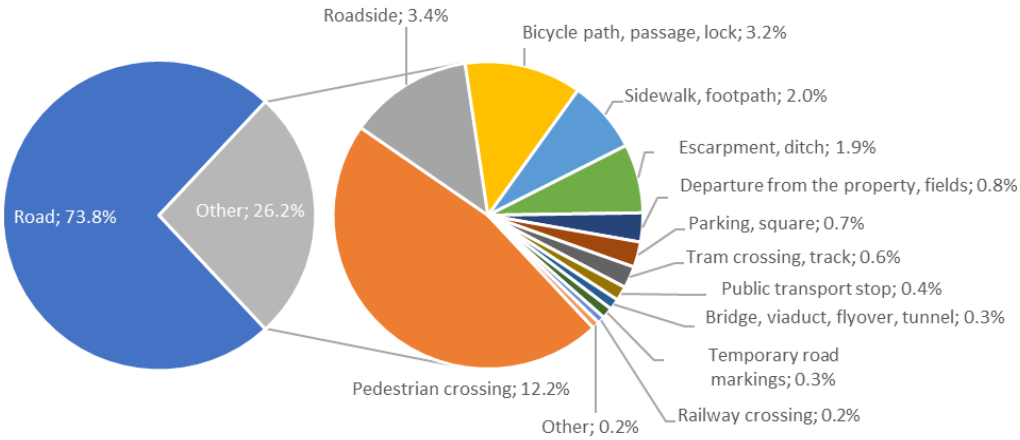


Figure 5. Road accidents in 2019 in Poland by place of their occurrence.

The report [43] also refers to the statistics for 2020. An important factor in road safety in 2020 was undoubtedly the coronavirus. COVID-19, despite all its negative effects around the world, has brought with it an unexpected, significant decrease in the number of road fatalities in countries where forced isolation has been introduced.

4.2. Road Safety Survey Analysis

The survey was aimed at verifying the opinion of road users regarding the safety of children and young people on the road and examining the level of satisfaction of respondents with pavements and bicycle paths in their living area. Initially, the research was carried out with the use of social media [44], but it was later extended. The research was conducted in the period from May to December 2020 with 217 respondents, located in the southern part of Poland, which is characterised by the highly urbanised area of Silesian Metropolis.

The structure of the research sample included 71% women and 29% men, who expressed opinions on children and their safety. The most numerous group (52%) were people aged 18–30, 19% of the people were aged 31–45, 16% were over 45 and the least numerous (13%) were people under 18.

In the survey, 199 people out of all respondents admitted that they have minors in their families, broken down as in Figure 6. According to the Central Statistical Office in Poland, out of 38.38 million inhabitants, there are approximately 9.6 million children, of whom people aged from 0 to 6 years old comprise 2.7 million, and 6.9 million minors are from 7 to 17 years old, i.e., 18% of the population of Poland [45]. In the first and largest group, 36.9% of the respondents have children aged 0–6 in their family. It is worth emphasising the additional responsibility of adults resulting from Polish law, which states that a child under the age of 7 may use the road only under the care of a person who has reached the age of 10 [46]. The second group of respondents (34.1%) indicated that they have young people aged 15–17 in their families. Children aged 7 to 14 live in families of 29.0% of the respondents.

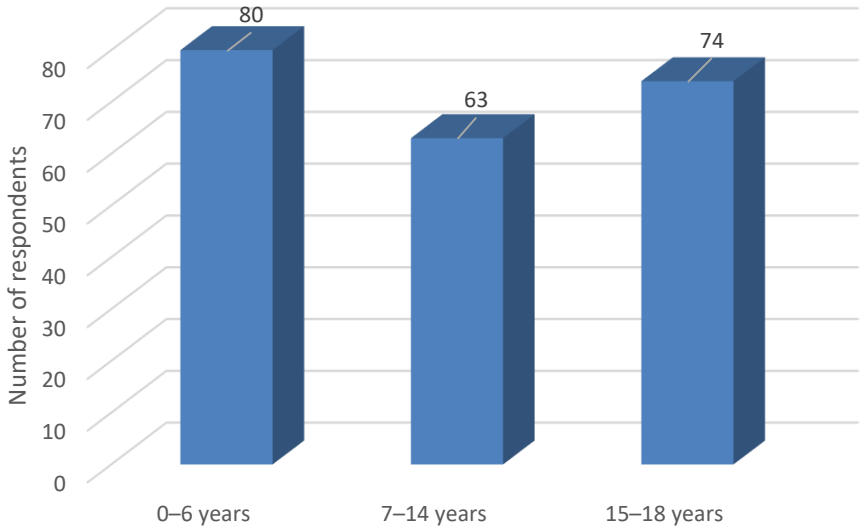


Figure 6. The number of individual age groups of children and adolescents in the respondents' families.

Another survey question concerned the share of respondents in road traffic. The largest group of people represents car drivers (118 people). The next largest group are pedestrians—81 people, which constitute 38% of the total. Only 8% of the respondents most often participate in road traffic as cyclists (18 people). It should also be noted that the greatest number of people who marked this answer were under 18 years of age. The next question sounded quite controversial, but the results of the interviewees' opinions are even more shocking: 179 people think that children are often the perpetrators of road accidents, and only 38 think the opposite. This is clearly an erroneous opinion in the light of the statistics presented above, in which the group of the most frequent perpetrators of road accidents are people over 60 years of age and not children and adolescents.

Another question in the survey concerned the place where road accidents caused by minors most often occur (see Figure 7). The vast majority indicated pedestrian crossings as most dangerous and roads that predominate in official statistics. Much fewer people consider sidewalks and bicycle paths to be dangerous places. It can therefore be concluded that the respondents intuitively indicated the most dangerous places, not disregarding official statistics, which may also be influenced by information about accidents communicated to the public by the mass media. The respondents are aware that minors are often the perpetrators of accidents not only on the road and at pedestrian crossings, but also on sidewalks and bicycle paths.

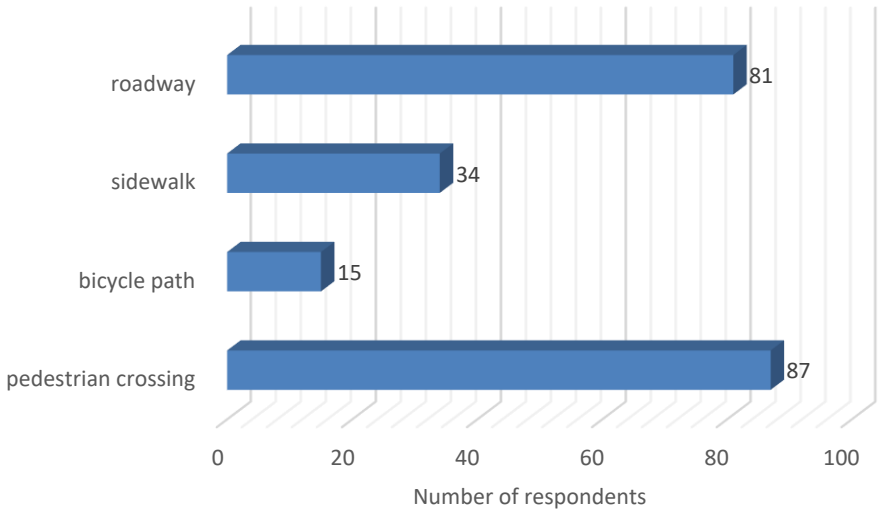


Figure 7. Place of the occurrence of road accidents according to the respondents.

In the next part of the study, questions were asked about the elements of road infrastructure and their impact on the residents' sense of safety. Unfortunately, as many as 77% of the respondents believe that there is not enough protective equipment in the locality where they live (e.g., protective barriers at sidewalks, additional signage at schools, hospitals, etc.). Another question concerned the assessment of the quality of sidewalks and bicycle paths. The majority of respondents (129 people) believe that the level of satisfaction with the quality of road infrastructure is low. Apart from pedestrians, the right to use sidewalks and pedestrian paths is also allowed for:

- People in a wheelchair,
- People pushing a bicycle, moped, motorcycle and electric scooter,
- People pushing a pram,
- Children up to 10 years of age on a bicycle, under the supervision of an adult.

In addition, it should be noted that, in special situations, a cyclist may also be on the pavement, but they must give way to pedestrians.

The last part of the questionnaire requested suggestions for improving safety in places where children are most at risk. It was possible to select multiple answers and submit your own ideas. As can be seen in Figure 8, the majority of 58% believe that infrastructure should be repaired or modernised, for example: adjusted in terms of width, and removing dangerous objects (poles, road signs or advertisements). Some 37% of respondents believe that sidewalks and bicycle paths should be developed. In the suggestions, which were supplemented by 11 participants in the study, the most frequently mentioned solutions in the field of road repair indicated the elimination of defects in the road and ruts. According to the indications, the problem is also the numerous manholes in residential areas, which are often below the road level and cause trouble for drivers. The last suggestion was to increase educational campaigns promoting the correct behaviour of children on the

roads. Summing up, it can be stated that the modernisation of the road infrastructure may significantly affect the safety level of the inhabitants of the southern part of Poland.

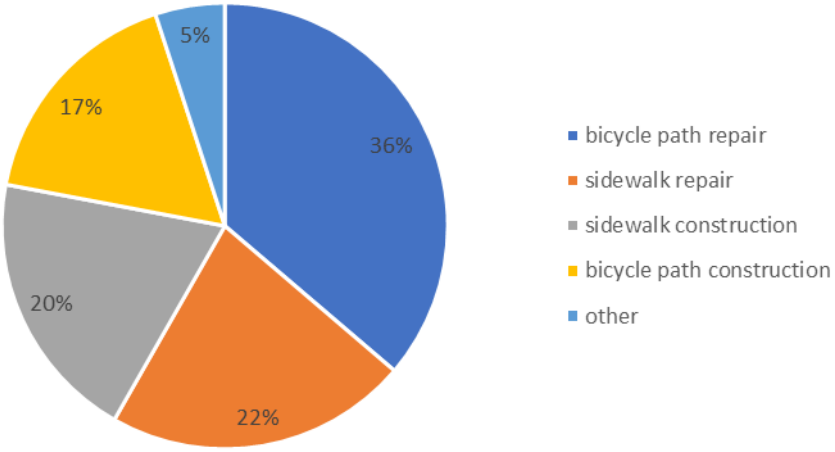


Figure 8. Suggestions for improving the safety of road infrastructure.

Summarising the research, the survey managed to explain that the respondents are aware that minors are often the perpetrators of road accidents on roads, sidewalks and bicycle roads. According to the results of the respondents, it was also shown that, in southern Poland, there is an insufficient amount of protective resources for pedestrians as well as sidewalks and bicycle paths that do not meet the respondents' expectations. In addition, the results showed that the modernisation of the road infrastructure (sidewalks, crossings and bicycle paths) may significantly affect the level of their satisfaction. It is recommended that such surveys are repeated after modernisation, or sequentially, in the future to check the level of satisfaction and the development of road infrastructure.

It is hopeful that, in 2020, the Polish government announced the launch of a new programme aimed at improving the quality of road infrastructure called 'Safe Infrastructure'. By introducing new investment, it is planned to renovate roads, pavements and bicycle paths. The activities of the programme will also focus on educating children and adolescents on the rules of the road. All activities included in the programme are to be implemented by the end of 2025.

5. Road Infrastructure Improvements to Prevent Accidents

In this section, the various infrastructure solutions used to increase the safety of road users, with particular emphasis on children, will be presented.

5.1. Infrastructural Solutions Increasing the Safety of Children at School Crossings

In Poland, vehicles often drive on roads near primary and secondary schools or kindergartens. This arrangement is very convenient for parents and guardians who can take their children to school by car before work. On such roads, there are usually special warning signs for drivers. Many schools also employ a 'children's crossing guard' to help students walk over the pedestrian crossings during busy hours before and after school, by stopping traffic on the road (Figure 9a). Such a solution does not require additional costs related to infrastructure and is associated only with organisational changes and personnel costs. Even though such a solution is very effective when it comes to the safety of children on the road, not all cities in Poland employ guards because it is quite an expensive way to protect children during the school year.

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

(**c**) (**d**)

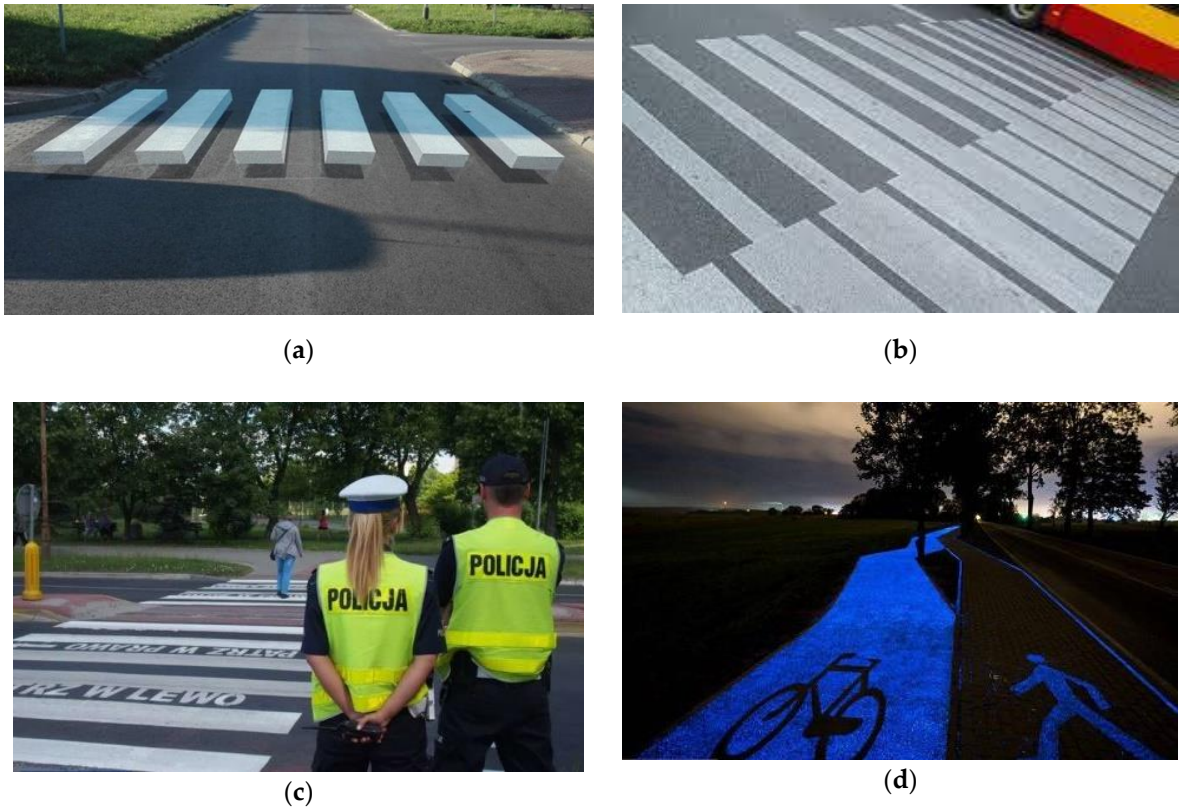
Figure 9. Exemplary solutions increasing the safety of children at school crossings: (**a**) Children's crossing guard. Reprinted with permission from ref. [47]. Copyright 2017 Urząd Miejski w Wolborzu [47], (**b**) Children's crossing. Reprinted with permission from ref. [48]. Copyright: Simon McGill (Getty Images), (**c**) A plaster figure imitating a road-crossing child. Reprinted with permission from ref. [49]. Copyright 2017 Depo.ua, (**d**) Plastic model of a girl crossing the road. Reprinted with permission from ref. [50]. Copyright 2020 Екатерина Романова (Комсомольская правда).

Another way is to design special Children Crossing signs with warning flags (Figure 9b) or light signals, ordering drivers to stop when the signal is flashing. Another solution is the positioning of a life-size plaster figure, imitating a child walking through a pedestrian crossing (Figure 9c), as found in Ukraine, or plastic models, in Russia (Figure 9d). The figures are up to 1.60 m in size and in the shape of not only small children, but also teenagers. Such mannequins are different, and it is hard to find two similar ones. This caused aggression on the part of some drivers, because they lost extra time every time they stopped at such a crossing. To make matters worse, drivers accustomed to fake children are not then sufficiently vigilant with real children walking on zebra crossings. Despite the fact that, in many cities, it has been decided to eliminate this type of dummy, these unique solutions can still be seen in some places in Russia and Kazakhstan.

5.2. Infrastructural Solutions Increasing the Visibility of Crossings

An interesting solution to increase the visibility of pedestrian crossings is their modification with special stripe painting, which, since 2017, began to be tested in Scandinavian countries and France. Drivers approaching such a 3D transition have the impression that the lanes are in the form of a three-dimensional solid lying on the street, which forces you to reduce speed. This solution was also used in Poland in 2018 (Figure 10a). Other, even more artistic designs were also tested around the world, such as those presented in a Warsaw

pedestrian crosswalk designed in the style of a piano in order to commemorate Chopin's 200th birthday (Figure 10b). However, research on the example of a piano/keyboard-styled pedestrian crossing (3DPKcrossing) in Chiang Mai in Thailand over a period of 12 weeks showed that vehicle speeds decreased significantly after the 3DPK crossing was installed for the first three weeks [51]. After that, the vehicle speeds slightly increased back to the same level as before the installation.



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

(**c**) (**d**)

Figure 10. Examples of improving the visibility of pedestrian crossings: (**a**) Three-dimensional crossing, (**b**) piano/keyboard-styled pedestrian crossing (3DPKcrossing), (**c**) pedestrian crossings with hints. Reprinted with permission from ref. [52]. Copyright 2020 Lubuska Policja], (**d**) bicycle road and sidewalk visible at night.

Another example are crossings with hints for pedestrians (e.g., look left, look right) in the form of additional horizontal markings (Figure 10c). This is to draw attention to pedestrians when crossing the street and may reduce the number of collisions in the area of pedestrian crossings.

Another example of an investment improving visibility is a bicycle path that shines at night, which was the first to be put into use in Poland in 2016. It is completely self-sufficient and ecological. Its surface includes so-called phosphors. These are synthetic substances that are charged by daylight and then gradually release the stored energy at night, glowing blue (Figure 10d).

5.3. Advanced Infrastructural Solutions

Another solution, already widely used in Poland, is the use of point reflective elements at pedestrian crossings, with additional use of motion sensors (known as 'cat's eyes'), typically used in smart cities. A specially mounted motion sensor that reacts to an approaching pedestrian or cyclist will activate an increased frequency of pulsing (flashing) of the LED diodes (Figure 11). The use of reflective elements and active elements in the form of diodes as an additional light source significantly improves the visibility of these elements. Active point reflectors have luminous diode elements powered by built-in batteries or capacitors of high capacity. The use of road markers with narrow lighting angles allows their visibility,

even from a distance of 1000 m. The visibility of the marking from such a large distance allows the driver to react earlier and drive safer. A special chemically hardening mass is used for the assembly of the markers, which ensures their perfect fixing.

Figure 11. Advanced design of pedestrian crossings: active crossing equipped with 'cat's eyes'.

The use of an unusual installation from Québec in Canada could turn out to be innovative and it consists of yellow panels that imitate the stripes on a pedestrian crossing. The panels go up as the car approaches them. Then, the drivers' eyes will see nearly two-meter high plates [53]. They do not appear on the street permanently, each time they are lifted by an operator who could assess the safety and legitimacy of lifting the panels with his own eyes. The panels bear the inscription, in French, that the crossings are there to protect pedestrians and they thank any driver who stops in front of them to give way to people crossing the road. The design is part of the 2019 campaign to improve road safety by Le société de l'assurance automobile du Québec (SAAQ), which is encouraging drivers to be more aware of their responsibilities in keeping pedestrians safe.

The above-mentioned proposals for improvements in the field of road infrastructure are aimed at bringing the following safety benefits:

- Reducing the number of road accidents and fatalities by increasing the visibility of road users or reducing the speed of vehicles.
- Reduction of external transport costs, resulting from the necessity of compensation costs of hospital treatment, rehabilitation of the disabled as well as disability benefits costs.
- Improving the sense of security for pedestrians and bicycle users and, therefore, more frequent use of these forms of movement (health and environmental benefits).
- Creating a better environment for residents, related to pleasure and comfort, by the design of infrastructural elements, such as road lighting.

Assessment of the road infrastructure solutions for preventing accidents involving children is a difficult task due to their diversity. Therefore, the following evaluation criteria (and assessment weights) were considered for their evaluation, enabling the determination of the importance of a given criterion when making decisions regarding the modernisation of road infrastructure:

(a) Implementation cost (0.2), defining investment outlays for the implementation of a new solution for the existing road infrastructure.
(b) Maintenance cost (0.2), associated with the need to incur additional costs throughout the year of using the solution or taking care not to deteriorate its condition by modernising, painting, etc.
(c) Solution effectiveness (0.2), reflects the effectiveness of the application in the prevention of road accidents.
(d) Universal application (0.15), related to the use of a given solution in various types of roads and buildings.
(e) Solution duration (0.1), characterises the long service life of a given solution.

(f) Aesthetic qualities (0.05), reflects the need not to disturb the visual harmony in line with the smart city idea.

All of the above-mentioned infrastructural solutions in the field of improving the safety of children were assessed according to the criteria discussed. The weighted assessment method was used, in which the assessment of individual criteria, on a scale of 1–10 (1—lowest, 10—highest), was multiplied by the importance of the criterion. A summary of the grades is presented in Table 2.

Table 2. Multi-criteria assessment of infrastructural solutions increasing children's road safety.

Solution	Criteria						Total
	a	b	c	d	e	f	
Children crossing guards	0.40	0.20	1.60	0.75	0.80	0.25	4.00
Children crossing signs	1.00	1.60	1.20	1.50	0.60	0.25	6.15
Children's figure imitation	0.80	0.80	1.00	0.90	0.20	0.10	3.80
3D/special shape crossings	0.40	0.80	1.00	0.90	0.20	0.50	3.80
Fluorescent sidewalks and bicycle paths	0.40	1.60	1.60	1.50	0.80	0.50	6.40
Cat's eyes active crossings	0.20	1.60	1.60	1.20	1.00	0.50	6.10
Crosswalk safety barriers	0.20	1.60	2.00	0.75	1.00	0.10	5.65

The graphical form of the analysis results is shown in Figure 12, thus obtaining a ranking of infrastructural solutions that increase children's road safety.

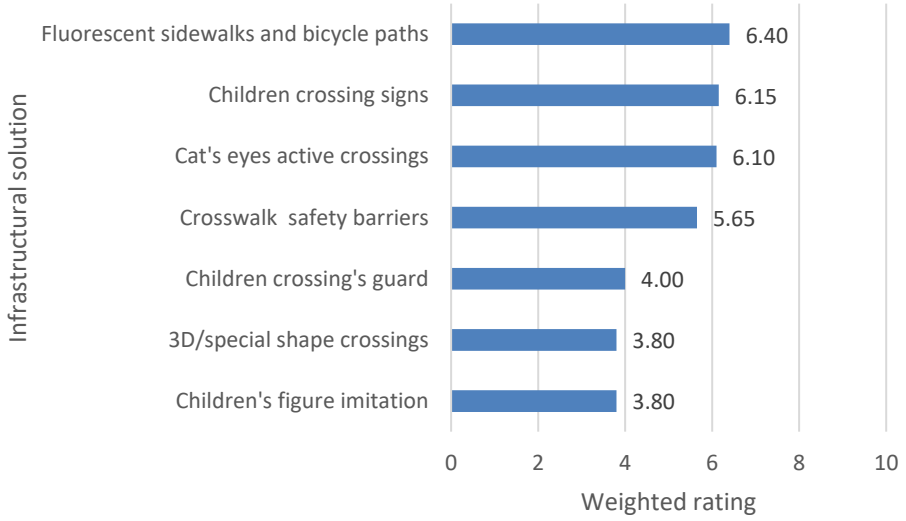


Figure 12. Ranking of infrastructural solutions increasing children's road safety.

Considering the most important selection criteria when modernising the road infrastructure, fluorescent sidewalks and bicycle paths seem to be the best solutions to be used in cities, mainly due to their low cost and effectiveness. Children crossing guards are very effective but can only protect children crossing the road while the guards are at work, and this solution is the most expensive. As part of the expansion of urban infrastructure, the use of solutions based on specially painted pedestrian crossings and figures imitating walking children are not recommended due to their ineffectiveness.

All of the examples presented have different implantation costs and different effectiveness, but it is worth considering that even one child's life may be saved by its use.

6. Conclusions

The behaviour of young road users should be considered in the development of injury prevention programmes, focusing on child and parent education and training, and by adapting the infrastructure of the urban environment to better meet their needs.

This study presented the level of safety of children and adolescents on the road in Poland and the level of satisfaction with the road infrastructure of road users, through the analysis of statistical data resulting from the survey. The key road safety resources for all pedestrian groups have also been listed and resources that directly affect the safety level of minors have been identified.

The survey made it possible to show that the respondents are aware that minors are often the perpetrators of road accidents on roads, sidewalks and bicycle lanes. According to the results of the respondents, it also turned out that, in the southern part of Poland, there is an insufficient amount of protective resources for pedestrians, as well as sidewalks and bicycle paths that do not meet the expectations of the respondents.

The road infrastructure solutions presented in this article aim at improving the safety of, especially, people crossing the road. Solutions can be distinguished as: increasing the safety of children at school crossings, improving the visibility and advanced specially designed crossings. The solutions were evaluated, considering selected criteria when modernising the road infrastructure, and a ranking list was prepared.

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