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Road Safety Barriers and the Safety of Road users – the Analysis of the Situation in Poland

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Abstract
Road safety barriers are a basic element of the road infrastructure aimed at improving the safety of road users. Design parameters and indications for assembly are strictly regulated by the GDDKiA (General Directorate for National Roads and Motorways) guidelines in accordance with the European standards. In Poland, the most commonly used barriers are thin-walled metal sheet barriers, rope barriers, and concrete ones. The types differ in terms of technical parameters and level of security they provide. One of the purposes of installing road safety barriers is to protect road users from hitting an obstacle in the vicinity of the road, and to protect people around the accident from the effects of an uncontrolled vehicle leaving the road. The effects of a collision caused by hitting a protective road barrier depend mainly on the type of the barrier and the vehicle. The authors made a detailed and interdisciplinary analysis of data on accidents resulting from hitting a road safety barrier, comparing them with information available in the literature, combining the technical aspects of the use of barriers with a medical description of the description of typical injuries.

Keywords: road safety barriers, damage, road safety, road accidents, risk of injury

1. ROAD SAFETY BARRIERS IN POLAND

Road safety barriers are a basic element of the road infrastructure aimed at improving the safety of road users. Their main goal is to absorb the impact energy while maintaining the vehicle on the road. This protects the passengers against the effects of a direct impact with an object in the vicinity of the road and, at the same time, prevents third persons in the vicinity of the road from being injured by the vehicle leaving the road out of control. In Poland, the main institution responsible for creating guidelines on the principles of using road safety barriers is GDDKiA (General Directorate for National Roads and Motorways). The latest guidelines, formulated in January 2014 based on the PN-EN 1317 standard, are intended to indicate the conditions and places of installation of barriers, according to the following principles:

- necessity - construction of road safety barriers only in places necessary for the safety of human life, strictly defined by the guidelines[1]
- optimization - selecting the best technical attributes and construction rules that provide the best chance of survival in a road accident and minimize the damage [1]

This approach makes it possible to reduce the number of barriers along the road to the minimum. Each physical structural element may be exposed to impacts by vehicles. Every such collision with a physical barrier carries a non-zero probability of a potential injury. This way, the number of accidents, the risk of serious injuries and of fatalities as a result of hitting a physical barrier can be minimized [1].

1.1 Parameters characterizing road safety barriers

The guidelines indicated by GDDKiA in order to avoid favouring the producers do not strictly define the shape, type and material of protective road barriers, instead, they provide the parameters that must be met in order to obtain approval enabling the product to be used in construction works.

- Containment level- the ability of road safety barriers to withstand an impact of a vehicle, which is dependent on the mass of the vehicle, the angle and speed of the impact. It is determined on the basis of crash tests (taking into account the above-mentioned variables) and presented on an ordinal scale by assigning it to the following classes:
  - Low: T_1, T_2, T_3

- Average: N_1, N_2,
- High: H_1, H_2, $H_{3,}$ L_1, L_2, L_3
- Very high: H_{4a}, H_{4b}, L_{4a}, L_{4b} [1–3]

Low containment level is permissible only for temporary barriers. The lowest containment level of permanent barriers is N_1 [1].

- Collision severity level - a theoretical parameter that allows for a preliminary estimation of the severity of physical injuries or the risk of death as a result of injuries caused by hitting a road safety barrier. It is expressed on a nominal scale (levels A, B and C) taking into account 2 factors:
  - ASI (Acceleration Severity Index) – an indicator used to determine the potential for occupant risk at the moment of impact. Directly proportional to the risk of injury. Exceeding the value of 1 indicates a significant risk of injury [1,4,5].
  - THIV (Theoretical Head Impact Velocity) – a value expressed in $^{km}/_{h}$, allowing assessment of the intensity of the impact of a person in the vehicle at the moment of colliding with a road safety barrier [1,6,7].

Tab. 1. Collision severity level,

Collision severity level	ASI	THIV [$^{km}/_{h}$]
A	$\leq$1,0	$\leq$ 33
B	1,0< ASI $\leq$ 1,4	$\leq$ 33
C	ASI$\leq$ 1,9	$\leq$ 33

Source: Wytyczne Stosowania Drogowych Barier Ochronnych na Drogach Karjowych wraz z załącznikami. GDDKiA; 2014 [1]

The most desirable impact severity level is level A, which provides the highest safety. Level B can be used only in exceptional and justified cases. Barriers with the impact severity level C are unacceptable to use.

Containment level and collision severity level are values that are completely independent from each other, which enables the construction of barriers with low containment level, which at the same time have a high collision severity level.

- Deformation of road safety barriers- characterized by 2 main parameters:
  - Standardized working width (W_N)- the maximum lateral distance between any part of the barrier facing the traffic and the maximum dynamic position [1]

- Standardized dynamic deflections (DN) - maximum lateral displacement of any point of the barrier face from the traffic side [1]

The stiffness parameters play one of the key roles win improving safety through road safety barriers. Too stiff barrier causes the vehicle to bounce and return to the lane, which could be hazardous for other road users. On the other hand, the use of barriers with low stiffness gives a potential chance of hitting an object behind the barrier [8,9].

In order to fulfil its function, the length of a road safety barrier must exceed the minimal required barrier length, which is defined for every model by its producer, based on crash and approval tests under the conditions specified by standard PN-EN-1317 [1-3]. The total length of a road safety barrier can be broken down into major components:

- the length of the initial terminal.
- the approach length- making it impossible to drive over the barrier and hit an obstacle or enter a danger zone.
- the length relative to the danger zone- equal to the length of the obstacle or a danger zone.
- the departure length- allowing to freely avoid an obstacle or a danger zone.
- the length of the final terminal[1].

Failing to meet the requirements concerning standard lengths and proportions between the components may cause a partial or complete loss of the protective properties of the barrier in relation to both passengers and third parties in the danger zone. It can also pose an additional threat to people in the vehicle.

Required behaviour of the barrier and the vehicle in a collision

- restraining and changing the direction of the vehicle, avoiding breaking of the longitudinal elements and disintegration of the road safety barrier
- no penetration of the vehicle interior by elements of the road safety barrier
- the vehicle may go over or under the road safety barrier with not more than one wheel.
- the vehicle must not overturn, either in or after the collision [1].

1.2 Indications concerning the places of installation of road safety barriers

GDDKiA guidelines clearly indicate the places where the installation of road safety barriers is required and what level of containment they need. It is determined on the basis of specialized algorithms and nomograms taking into account the computational/reliable speed (the permissible safe speed of vehicles in free traffic depends, inter alia, on the profiling and the number of bends, road width, road shoulder type) appropriate for a given type of road, projected traffic of vehicles, increased risk of vehicles leaving the road, the presence of danger zones and obstacles. However, two specific situations, which differ significantly in design indications, can be distinguished: barriers at the outer edge of the road and barriers on the lanes dividing the road [1].

1.3 Safety road barriers at the outer edge of the road

In this case, the key elements determining the need to build a road safety barrier are the presence of danger zones strictly defined by the guidelines. They are defined as places that have a potential influence on the safety of vehicle passengers, people in the vicinity, and objects; at the time of a vehicle leaving the road uncontrollably. The guidelines divide them into two main classes determined by the more vulnerable subject:

- danger zone - the area on the road or in its vicinity where there is a risk to bystanders, regardless of the risk to the car passengers (e.g. public utility facilities)
- obstacle - an object on the road or in its vicinity that poses a hazard to vehicle passengers in the event of a collision [1]

In each situation, different barrier parameters are required, determined by calculations and nomograms taking into account, inter alia, designed speed of the road, the road-place level difference and the boundary distances from which the barrier should be set. If the ambient conditions allow, the limit distance should be at least 3.5 meters, thus exceeding the value of the largest level of the working width of the barriers [1].

1.4 Road safety barriers between the lanes

The main purpose of barriers in between traffic lanes is to prevent vehicles from getting to the other side of them. The opposite lane of a dual carriageway is always a danger zone, therefore, on the lanes dividing carriageways with the design speed of $(V_{Obl.}) \geq 50^{\mathrm{km}}$, it is necessary to use road safety barriers, moreover, the dividing lane may contain additional hazardous elements, in such case, barriers should be constructed, while taking into account the presence of the obstacle. The diverse architecture of the dividing lane implies a variety of barriers that can be used in this area. The breakdown is based on the number of frontal planes that may be involved in the collision. Double-sided barriers should be used mainly in the middle of the dividing strip, however, if this is not possible for various reasons, it is permissible to move them away from the axis. One-sided barriers may exist in a form with joint or separate impact. Barriers with a separate effect are placed at a distance greater than W_N, a joint impact requires a spacing smaller than W_N [1].

2. TYPES OF SAFETY ROAD BARRIERS USED IN POLAND

The conditions defined by the legislator, specifying the minimum construction requirements that must be met by road safety barriers, allow for quite a wide possibility of modification with a view to improving the broadly understood effectiveness. The currently used construction solutions for steel road safety barriers are bar-beam or tension-bar structures. In Poland, road safety barriers made of thin-walled steel profiles joined with screws are by far the most popular [1]. The usefulness of the road safety barrier during a collision is determined by the legal conditions that must be met and a separate indicator that can be controlled by the design engineer - energy absorption [10, 11]. The following factors affect the energy absorption index: the material from which the structure is made and the geometric shape of structural elements. The behaviour of the structure during a collision depends, therefore, both on the construction material used, as well as on the geometry of the components and the entire structure. In order to choose a proper type of road safety barrier, the design engineer has to take into consideration all of the before mentioned aspects (containment level, collision severity level and deformation). Depending on type of the road, mass of the vehicle, the angle and speed of the impact, one has to choose type (profile) of the steel guide (A, B or W) and distance between posts, supporting the barrier. That procedure leads to achieving the best safety results. After selecting a barrier, a safety test must be conducted. Depending on the aspects, an appropriate type of crash test is chosen [1]. The tests are performed under particular conditions, which may not correspond to reality. Therefore, it is right to continue research aimed at improving the effectiveness of protective barriers subjected to dynamic forces. The industry database is rich in studies on the mechanics of thin-walled structures [12–18] as well as in material tests, including modelling their mechanical properties [17, 19, 20]. You can also find many works related to the study of layered structures with different properties of individual layers [21], which are often characterized by high energy dissipation capacity. There are also studies of already functioning road safety barriers with the use of simulation and experimental methods [22–25], the use of analytical methods in the mechanics of vehicle collisions with energy-consuming barriers is not that popular. Therefore, it can be concluded that the research approach to the construction problem of energy-consuming protective barriers is still a topical task, especially due to the diverse, dynamic aspect of the forces acting on the structure and the inevitable progress in vehicle construction[26]. Due to the many design solutions and the variety of materials used in the production of road safety barriers (in Poland, only S235 steel is used, most likely) only a general description is possible, divided into 3 main groups of barriers used in Poland:

- **concrete road safety barriers**- usually solid concrete cast, barriers with the lowest energy absorption, the impact energy is absorbed by the horizontal displacement of the barrier or a set of barriers, they indirectly retain their function in insulation, they do not have support posts and sharp edges, usually with a low level of restraint, the highest probability of rebounding the vehicle [24–26].
- **steel safety barriers with a profile / guide** - made of an open sheet metal profile with a cross-section resembling the letter Σ, supported by posts. These are barriers with indirect energy absorption, impact force is absorbed by the steel profile displacement, they fulfil their function after reaching the length critical for the system, they include support posts and sharp edges [27–30].
- **rope safety barriers**- made of 3 to 5 steel cables of low or high tension suspended on support posts, barriers with relatively the highest energy absorption. Impact energy is absorbed by increasing cable tension and friction between the lines of which the rope is composed, making use of the shock-absorbing systems at anchor points, and breaking support poles. They include sharp edges, the installation cost is low [27, 28, 31].

The injury analysis of road accident casualties showcases a number of imperfections in the currently used road safety barrier constructions. The most important ones are:

- a motorcyclist hitting the structural elements of road safety barriers suffers particularly serious injuries when the victim's body comes into contact with sharp edges of beams, posts and connectors,
- after being struck by a vehicle, a pedestrian hitting the structural elements off road safety barriers suffers severe injuries, as a result of contact with sharp edges of beams, posts and connectors [1].

It is necessary to undertake research to develop new constructional solutions for energy absorbing elements of road infrastructure, in order to reduce the potential risk, which is often a result of imperfections in the commonly used technical solutions.

Beside listed 3 groups of barriers used in Poland there are some conceptions that may impact improving road safety. One of them is a smart system called AIBDiM (Active Intelligent Road and Bridge Barriers). The system consists of: cameras, registering moving vehicles; a steel structure filled with composite materials and tanks attached to the structure. The working principle is simple, cameras analyse type of vehicle moving in the direction of the barrier and give the information to electronic system, which fills the tank with proper amount of liquid. In case of an accident the barrier with liquid has the most potential of absorbing the impact. The prototype of this system may be found near Bydgoszcz, Poland. Moreover, a new solution was introduced in South Korea. Existing steel barriers are reinforced with barrels made of plastic material. The barrels, mounted that they may rotate in their own axis, are meant to redirect the impact, reduce the energy of the impact and allow the vehicle to slow down smoothly. These solutions may lead to improvement in the road safety.

3. STATISTICS OF ACCIDENTS CAUSED BY HITTING THE ROAD SAFETY BARRIERS, IN POLAND

The analysis of the reports and statistics of the Polish Police Headquarters (Komenda Główna Policji – KGP) for the years 2009-2020 concerning road accidents shows that the number of accidents caused by hitting a road safety barrier annually stops at a relatively constant level, while their percentage share in relation to the total number of accidents is increasing [32].

A similar trend can also be observed in the statistics of people killed and injured in accidents caused by hitting a road safety barrier. In each of these cases, despite maintaining a relatively constant number of killed and injured, their percentage share in relation to the total number of accidents is increasing [32].

In years 2009-2020 hitting a road safety barrier oscillated between 10th and 11th places on the list of the most common causes of road accidents [32].

When it comes to the road safety barrier accidents, the most common causes in the analysed time period were not adjusting the speed to traffic conditions, followed by fatigue/falling asleep and unsafe lane changing [32, 33].

Compared to other road users, motorcyclists are more likely to be seriously injured [34]. The probability of dying as a result of a traffic accident is 30 to 44 times greater, and the risk of a severe injury is 20 to 56 times greater than for passengers of other vehicles in relation to the distance travelled.[34–40]. In 2013-2018, in 249 accidents involving motorcyclists, the number of casualties was 250. This suggests that the victims of the accidents are mainly the riders of the vehicle, a small percentage are passengers. The percentage of deaths in relation to the total number of casualties of an accident caused by hitting a road safety barrier among the motorcyclists is 26%. It means that in the event of a collision with a road safety barrier, 1 in 4 accidents ends in the death of a motorcyclist. This is due to the direct exposure of the rider's body to the elements of the barrier [35]. The damage profile depends mainly on the type of barrier [35]. The speed and angle of approach as well as the use of protective clothing also have a significant influence on the risk and type of injuries sustained [27, 35]. In 2013-2018, in 1,521 accidents involving car passengers, the number of victims was 2,161. In the group of people traveling in passenger vehicles, the percentage of deaths in relation to the total number of injured is 5.6%. The noticeable decrease in the percentage of deaths is due to the protective effect of the vehicle body [9, 34].

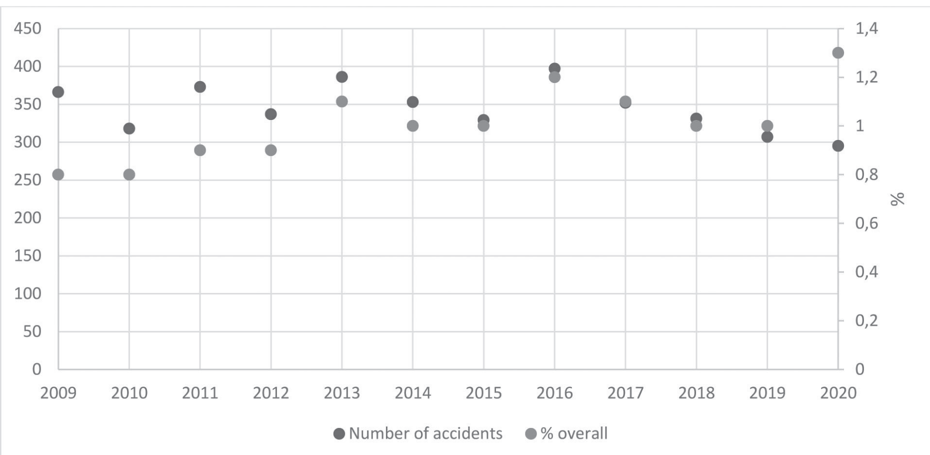

Fig. 1. Number of accidents caused by hitting a road safety barrier, KGP data [32]

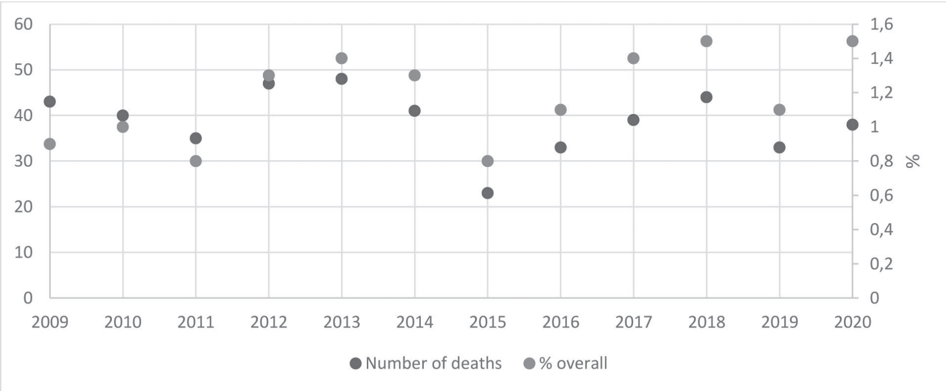

Fig. 2. Number of fatalities in accidents caused by hitting a road safety barrier, KGP data[32]

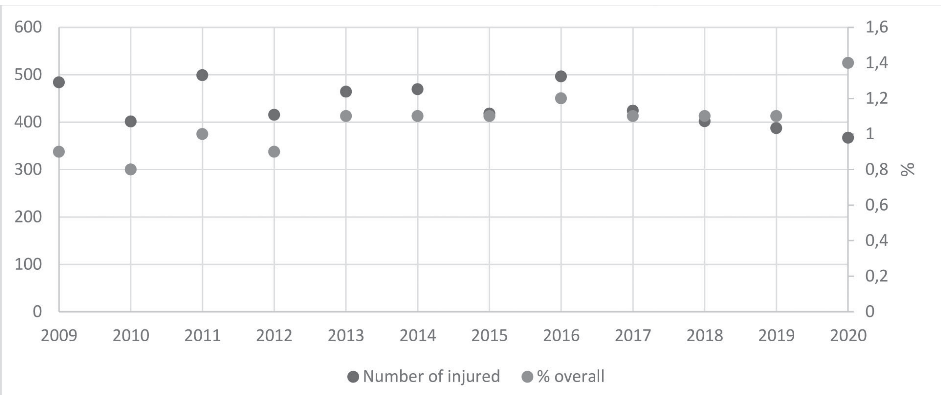

Fig. 3. Number of casualties in accidents caused by hitting a road safety barrier, KGP data [32]

Tab. 2 Reasons for hitting the protective barrier by drivers of passenger cars, KGP ta[32]

Driver's action	Number of accidents						Number of fatalities in accidents						Number of casualties in accidents					
	2013	2014	2015	2016	2017	2018	2013	2014	2015	2016	2017	2018	2013	2014	2015	2016	2017	2018
Sudden braking	2		2			2	0		0			0	2		3			3
Other			1	18	26	16			1	2	3	4			1	21	26	16
Driving on the wrong side of the road			1						0						2			
Not adjusting the speed to road conditions	206	185	182	206	201	182	20	19	10	14	20	17	277	275	249	256	248	248
Unsafe avoiding	1			1						0			1			1		
Unsafe turning	1	3	1	3	1	3				0	0	0	1	3	1	5	1	4
Unsafe evading	1		1		2	1					0	1	1		1		4	1
Unsafe overtaking	3	8	7	6	3	3	0	0	1	0	0	0	4	8	9	12	4	4
Unsafe turning back					1						0						3	
Unsafe lane changing	10	9	6	10	15	14				0	3	1	14	10	8	11	18	18
Ignoring road signs and signals		3	1	3				0	0	0				4	1	5		
Not giving priority to pedestrians	1						0						1					
Not giving priority to other vehicles	8	4	2	5	9	2				0	1	0	8	7	4	6	9	3
Not leaving enough space between vehicles	1	1	1	3	2	1				0	0	0	1	2	1	3	2	2
Fatigue, falling asleep	26	28	22	29	15	10	1	3	0	0	0	0	37	45	37	42	33	13

Tab. 3 comparison of the number of accidents, casualties and deaths as a result of itting a road safety barrier in the group of passenger vehicles and motorcycles, KGP data[32]

Vehicle type	Number of accidents						Number of fatalities in accidents						Number of casualties in accidents					
	2013	2014	2015	2016	2017	2018	2013	2014	2015	2016	2017	2018	2013	2014	2015	2016	2017	2018
Motorcycle	44	48	28	48	23	45	13	12	7	13	4	16	32	40	23	35	20	35
Passenger car	260	241	227	284	275	234	21	22	12	16	27	23	347	354	317	362	348	312

4. FACTORS INFLUENCING THE PROBABILITY OF A VEHICLE COLLIDING WITH A ROAD SAFETY BARRIER AND THE EXTENT OF INJURIES

Vehicle type- drivers of motorbike vehicles are a group more exposed to serious injuries as a result of hitting the road safety barrier than those traveling by passenger vehicles [34, 35, 41, 42]

Barrier type- for users of passenger vehicles, a collision with a rope safety barrier increases the chances of sustaining only minor injuries in relation to a collision with a concrete barrier or one consisting of thin-walled metal profiles. The greatest likelihood of sustaining a major injury has colliding with a concrete barrier [28, 31, 43, 44]. The reverse relationship occurs in the group of motorcyclists [45]

Vehicle speed- directly proportional to the increase of the risk of a severe injury. This is due to the kinetic energy growing with the speed increase [31, 46–48]

Angle of impact- influencing the value and direction of the resultant force, as well as the fraction of kinetic energy used to deform the barrier and the vehicle body, consistent with the distribution of the vehicle's energy grid [8, 9, 45, 46, 49]

Use of seat belts/helmets- using them significantly increases the chances of reducing damage caused by hitting a barrier [29, 31, 41, 50–52]

Road profile- *the increase in the probability of serious injuries sustained as a result of hitting a barrier on a curved section of the road is explained by a greater collision angle and the danger of the vehicle going over the barrier in these places due to centrifugal force [8, 31, 46]*

Behaviour of the vehicle after impact- overturning the vehicle or crossing into an adjacent lane greatly increases the risk of a serious injury, in addition, in such a case there is a risk of other road users hitting the vehicle, which significantly increases the risk of serious injuries [8, 28, 31, 41]

Alcohol / drugs / medications- depending on the substance and its dose, the use may translate into a greater tendency to risky behaviour on the road, slower reaction time or weaken one's concentration, which directly increases the risk of sustaining a severe injury [8, 50, 53–56]

Time of day- statistical analyses indicate a higher probability of serious injuries sustained as a result of an incident involving a road safety barrier when the incident occurs at night. The probable explanation is the limited visibility, which directly affects the reaction time. One more factor could be reduced traffic in comparison to the daytime, which encourages drivers to develop higher speeds [29, 31]

Day of the week- a trend of more fatal accidents during weekends can be observed due to recreational and "weekend" vehicle use, which directly translates into less experienced driving [29, 41]

Road conditions- road conditions commonly considered to be difficult, e.g. rain, snow, fog, wet or icy road reduce the risk of serious injuries caused by running into a protective road barrier. This is explained by the fact that drivers adjust the speed to the driving conditions and are generally more focused [28, 31]

Type of bodywork- drivers of large pick-ups and larger vehicles are the least likely to sustain serious injuries after colliding with a road safety barrier, while motorcycle drivers are the most vulnerable [28, 57]

Gender, age, driving experience, predisposition to take risky actions [27, 29, 31, 51]

5. CONCLUSIONS

Improving the safety of road users in the face of an increasing number of motor vehicles is extremely important. Road safety barriers, as one of the basic permanent safety elements, are one of the key tools to achieve this goal. Further research is necessary to develop solutions that will improve the protective properties of barriers. It is particularly important to adapt road safety barriers in such a way that they provide greater protection to motorcyclists. It is possible to achieve such a result, for example, by the use of specialized energy-absorbing overlays on structural elements of barriers. One should remember about the necessity to systematically raise social awareness in the field of road safety. The problem of road safety is a complex problem that requires comprehensive solutions, possible only through the interdisciplinary cooperation of designers and medical professionals. This approach allows, through a detailed indication of injuries and showing the most dangerous elements for individual road users, the elimination of these elements by modifying the structure of road safety barriers. It is possible only when the medical documentation of the accident victims is analysed and compiled with the reconstruction of the course of the event. It is also necessary to conduct extensive retrospective studies of data describing the circumstances of accidents involving road safety barriers, which will enable precise understanding of the risk factors for the occurrence of an event.

REFERENCES

[1] Generalna Dyrekcja Dróg Krajowych i Autostrad, Wytyczne Stosowania Drogowych Barier Ochronnych na Drogach Krajowych wraz z załącznikami, GDDKiA, 2014.

[2] EN 1317-2: 2010 [2001]: Road restraint systems, Part 2: Performance classes, impact test acceptance criteria and test methods for safety barriers including vehicle parapets, 2010.

[3] EN 1317-1: 2010 [2001]: Road restraint systems, Part 1: Terminology and general criteria for test methods, 2010.

[4] Pawlak M., *The Acceleration Severity Index in the impact of a vehicle against permanent road equipment support structures*, "Mechanics Research Communications", 77 (2016)/10, pp. 21–28.

[5] Gabauer D., Gabler H. C., *Evaluation of Threshold Values of Acceleration Severity Index by Using Event Data Recorder Technology*, "Transportation Research Record: Journal of the Transportation Research Board", 1904 (2005)/1, pp. 37–45.

[6] Sturt R., Fell C., *The relationship of injury risk to accident severity in impacts with roadside barriers*, "International Journal of Crashworthiness", 14 (2009)/2, pp. 165–172.

[7] Montella A., Pernetti M., *Vehicle occupant impact severity in relation to real world impact conditions*, [in:] *Proceedings of the 2nd International Congress on New Technologies and Modeling Tools for Roads*, Florence 2004, pp. 1-14.

[8] Wicher J., *Bezpieczeństwo samochodów i ruchu drogowego*, Wydawnictwa Komunikacji i Łączności, Warszawa 2012.

[9] Prochowski L., *Podstawy rekonstrukcji wypadków drogowych*, Wydawnictwa Komunikacji i Łączności, Warszawa 2014.

[10] Gradkowski K., *Stałe urządzenia techniczne dróg: materiały do wykładów i ćwiczeń*, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2010.

[11] Gradkowski K., *Budowle urządzeń technicznych dróg i ulic*, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2013.

[12] Anbarasu M., *A numerical investigation of local - distortional - lateral - torsional buckling interaction of cold - formed steel lipped channel beams*, "Asian Journal of Civil Engineering", 18 (2017)/4, pp. 643–656.

[13] Kotełko M., Lis P., MacDonald M., *Load capacity probabilistic sensitivity analysis of thin-walled beams*, “Thin-Walled Structures”, 115 (2017)/6, pp. 142–153.

[14] Liang C., Wang C. J., Nguyen V. B., English M., Mynors D., *Experimental and numerical study on crashworthiness of cold-formed dimpled steel columns*, “Thin-Walled Structures”, 112 (2017)/3, pp. 83–91.

[15] Martins A. D., Camotim D., Gonçalves R., Dinis P. B., *On the mechanics of distortional-global interaction in fixed-ended columns*, “Thin-Walled Structures”, 123 (2018)/2, pp. 162–184.

[16] Trahair N. S., Papangelis J. P., *Lateral-distortional buckling of beams with hollow flanges and folded plate webs*, “Engineering Structures”, 163 (2018)/5, pp. 71–76.

[17] Obst M., Kurpisz D., Paczos P., *The experimental and analytical investigations of torsion phenomenon of thin-walled cold formed channel beams subjected to four-point bending*, “Thin-Walled Structures”, 106 (2016)/9, pp. 179–186.

[18] Vignjevic R., Liang C., Hughes K., Brown J. C., De Vuyst T., Djordjevic N. et al., *A numerical study on the influence of internal corrugated reinforcements on the biaxial bending collapse of thin-walled beams*, “Thin-Walled Structures”, 144 (2019)/11, pp. 106277 (1-12).

[19] Wegner T., Kurpisz D., *An energy-based method in phenomenological description of mechanical properties of nonlinear materials under plane stress*, “Journal of Theoretical and Applied Mechanics”, 55 (2017)/1, pp. 129-139.

[20] Kurpisz D., Obst M., *The energetic and experimental based approach to description of basic material characteristics and mechanical properties of selected polymers*, “Journal of Theoretical and Applied Mechanics”, 58 (2020)/1, pp. 183–193.

[21] Magnucki K., *Bending of symmetrically sandwich beams and I-beams – Analytical study*, “International Journal of Mechanical Sciences”, 150 (2019)/1, pp. 411–419.

[22] Barnat W., Bogusz P., Dziewulski P., Gieleta R., Kiczko A., Klasztorny M., Niezgoda T., Ochelski S., *Experimental validation of the numerical model of car impact on a road barrier*, “Journal of KONES Powertrain and Transport”, 17 (2010)/1, pp. 1-11.

[23] Niezgoda T., Barnat W., *Analiza podatnych elementów kompozytowych w zastosowaniu do poprawy energochłonności barier drogowych*, “Biuletyn Wojskowej Akademii Technicznej”, 55 (2006)/4, pp. 21-43.

[24] Niezgoda T., Ochelski S., Klasztorny M., Barnat W., Kiczko A., Dziewulski P., *Experimental- numerical analysis of steel- foam energy- absorbing panels for road barriers modernization*, “Journal of KONES Powertrain and Transport”, 17 (2010)/1, pp. 309-315.

[25] Niezgoda T., Barnat W., Dziewulski P., *Numerical analysis of road infrastructure components on an example of SP -01, SP -04 and SP –09 barriers*, "Journal of KONES Powertrain and Transport", 14 (2007)/3.

[26] Dobrovolny C. S., Geary G., Dixon K., Manser M., Chauhan J., *Addressing the Motorcyclist Advisory Council Recommendations: Synthesis on Barrier Design for Motorcyclists Safety*, Texas A&M Transportation Institute, May 1, 2021, FHWA-SA-21-069 – https://rosap.ntl.bts.gov/view/dot/56065

[27] Zou Y., Tarko A. P., Chen E., Romero M. A., *Effectiveness of cable barriers, guardrails, and concrete barrier walls in reducing the risk of injury*, "Accident Analysis & Prevention", 72 (2014)/11, pp. 55–65.

[28] Russo B. J., Savolainen P. T., *A comparison of freeway median crash frequency, severity, and barrier strike outcomes by median barrier type*, "Accident Analysis & Prevention", 117 (2018)/8, pp. 216–224.

[29] Margiotta G., Calvisi G., Carnevali E., Bacci M., Gabbrielli M., *A fatal crash against guardrail. Report of a case and considerations about safety of roadway barriers in Italy*, "Revista de Medicina Legala", 23 (2015)/3, pp. 5–8.

[30] Obst M., Rodak M., Paczos P. R., *Limit load of cold formed thin-walled nonstandard channel beams*, "Journal of Theoretical and Applied Mechanics", 54 (2016)/4, pp. 1369-1377.

[31] Hu W., Donnell E. T., *Median barrier crash severity: Some new insights*, "Accident Analysis & Prevention", 42 (2010)/11, pp. 1697–1704.

[32] Komenda Główna Policji BRD, WYPADKI DROGOWE W POLSCE. Statystyki zebrane z lat 2009-2020, Komenda Główna Policji, 2021.

[33] Żaba C., Świderski P., Mularski A., Żaba Z., *Obrażenia spowodowane kontaktem z drogowymi barierami ochronnymi*, [in:] *XVI Konferencja Problemy Rekonstrukcji Wypadków Drogowych*, red. Unarski J., Series "Paragraf na Drodze", Wydawnictwo Instytutu Ekspertyz Sądowych, Kraków 2019, pp. 311–319.

[34] Keall M. D., Newstead S., *Analysis of factors that increase motorcycle rider risk compared to car driver risk*, "Accident Analysis & Prevention", 49 (2012)/11, pp. 23–29.

[35] Bambach M. R., Grzebieta R. H., McIntosh A. S., *Injury typology of fatal motorcycle collisions with roadside barriers in Australia and New Zealand*, "Accident Analysis & Prevention", 49 (2012)/11, pp. 253–260.

[36] DITRDLG, Fatal and serious road crashes involving motorcyclists. Research and Analysis Report, Road Safety Monograph 20. Department of Infrastructure, Transport, Regional Development and Local Government, Australia 2008.

[37] EuroRap., Barriers to Change: Designing Safe Roads For Motorcyclists, European Road Assessment Program, Basingstoke Hampshire, UK, Publication Number 01/08, 2008.

[38] NHTSA, Traffic Safety Facts, Motorcycles, 2008 Data. DOT HS 811 159, National Center for Statistics and Analysis, 2008.

[39] Park G.-J., Shin J., Kim S.-C., Na D.-S., Lee H.-J., Kim H. et al., *Protective effect of helmet use on cervical injury in motorcycle crashes: A case–control study*, "Injury", 50 (2019)/3, pp. 657–662.

[40] Rzeźniczek P., Czesław Ż., *Charakterystyka obrażeń ofiar wypadków motocyklowych ze szczególnym uwzględnieniem obrażeń czaszkowo- mózgowych/Characteristics of motorcyclists' victims injuries with special focus on skull and brain injuries*, "Anestezjologia & Ratownictwo/Anaesthesiology & Rescue Medicine", 10 (2016)/1, pp. 363–369.

[41] Jama H. H., Grzebieta R. H., Friswell R., McIntosh A. S., *Characteristics of fatal motorcycle crashes into roadside safety barriers in Australia and New Zealand*, "Accident Analysis & Prevention", 43 (2011)/3, pp. 652–660.

[42] Daniello A., Gabler H. C., *Effect of Barrier Type on Injury Severity in Motorcycle-to-Barrier Collisions in North Carolina, Texas, and New Jersey*, "Transportation Research Record: Journal of the Transportation Research Board", 2262 (2011)/1, pp. 144–151.

[43] Hosseinpour M., Haleem K., *Examining crash injury severity and barrier-hit outcomes from cable barriers and strong-post guardrails on Alabama's interstate highways*, "Journal of Safety Research", 78 (2021)/7, pp. 157-169.

[44] Daniello A., Gabler H. C., *Characteristics of Injuries in Motorcycle-to-Barrier Collisions in Maryland*, "Transportation Research Record: Journal of the Transportation Research Board", 2281 (2012)/1, pp. 92–98.

[45] Berg F. A., Rücker P., Gärtner M., König J., *Motorcycle impacts into roadside barriers-Real-world accident studies, crash tests and simulations carried out in Germany and Australia*, [in:] *Proceedings of the Nineteenth International Conference on Enhanced Safety of Vehicles*, Washington DC 2005, pp. 1-13.

[46] Prochowski L., *Mechanika ruchu*, Wydawnictwa Komunikacji i Łączności, Warszawa 2016.

[47] Guzek M. J., *Niepewność w analizie wypadków drogowych*, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2016.

[48] Ibrahim M. K. A., Hamid H., Law T. H., Wong S. V., *Evaluating the effect of lane width and roadside configurations on speed, lateral position and likelihood of comfortable overtaking in exclusive motorcycle lane*, "Accident Analysis & Prevention", 111 (2018)/2, pp. 63–70.

[49] Daniello A., Cristino D., Gabler H. C., *Relationship between Rider Trajectory and Injury Outcome in Motorcycle-to-Barrier Crashes*, "Transportation Research Record: Journal of the Transportation Research Board", 2388 (2013)/1, pp. 47–53.

[50] Di Maio V. J. M., Di Maio D. J., Świątek B., Przybylski Z., Jurek T., Maksymowicz K. et al., *Medycyna sądowa*, Edra Urban & Partner, Wrocław 2018.

[51] Molan A. M., Rezapour M., Ksaibati K., *Modeling traffic barriers crash severity by considering the effect of traffic barrier dimensions*, "Journal of Modern Transportation", 27 (2019)/2, pp. 41–51.

[52] Liu B. C., Ivers R., Norton R., Boufous S., Blows S., Lo S. K., *Helmets for preventing injury in motorcycle riders*, "Cochrane Database of Systematic Reviews", (2008)/1.

[53] Valen A., Bogstrand S. T., Vindenes V., Frost J., Larsson M., Holtan A. et al., *Driver-related risk factors of fatal road traffic crashes associated with alcohol or drug impairment*, "Accident Analysis & Prevention", 131 (2019)/10, pp. 191–199.

[54] Żaba C., Dobosz T., Kis-Wojciechowska M., Kołowski J., Lorkiewicz-Muszyńska D., Marcinkowski J. T. et al., *Wybrane zagadnienia z medycyny sądowej*, Wydawnictwo Naukowe Uniwersytetu Medycznego im. Karola Marcinkowskiego, Poznań 2014.

[55] Raszeja S., Nasiłowski W., Markiewicz J., *Medycyna sądowa: podręcznik dla studentów*, Państwowy Zakład Wydawnictw Lekarskich, Warszawa 1993.

[56] Mutschler E., Droździk M., Kocić I., Pawlak D., Geisslinger G., Kroemer H. K. et al., *Farmakologia i toksykologia: podręcznik*, Wydawnictwo MedPharm Polska, Wrocław 2018.

[57] Mehrara Molan A., Rezapour M., Ksaibati K., *Investigating the relationship between crash severity, traffic barrier type, and vehicle type in crashes involving traffic barrier*, "Journal of Traffic and Transportation Engineering (English Edition)", 7 (2020)/1, pp. 125–36.

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