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Studying road restraint systems to develop new guidelines

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Abstract

Key to understanding the needs and tools of road infrastructure management for preventing run-off-road crashes or minimising their consequences, is to identify the hazards and sources of hazards caused by wrong or improper use of road safety devices and identify errors in the design, structure, construction and operation of road safety devices. Studying such an extended scope of the problem required fieldwork and surveys with road authorities, designers, road safety auditors and road maintenance services. An outline of new guidelines could only be developed after understanding the effects of restraint systems, the design, additional elements, type of road and safety barrier location on a road or engineering structure and the road and traffic conditions on their functionality and safety. The paper will present the preliminary results of this research (research project – ROSE). After an in-depth study of the literature, a comparative analysis was made of selected guidelines and principles of using road safety devices in nearly 40 countries from different continents. The parameters which were identified to influence the choice of safety barriers were divided into thematic groups. Two main categories were identified based on the theory of risk: probability and consequences. Probability included factors which, if present in the road cross-section, may make an accident more likely. Consequences included factors which increase the severity and consequences of an accident. One way to understand the functionality of road safety devices is to build numerical models and conduct simulation tests of virtual crash tests. While the literature on numerical road safety device studies includes plenty of detailed works, there are no cross-cutting papers to summarise the partial results of the work of many research teams and condense the theoretical formulations and numerical implementations for the purposes of crash test analysis. The paper will present a proposed approach to such work along with preliminary results of numerical studies for selected problems using road safety devices such as safety barriers on horizontal curves, the effect of kerbs on bridges or the location of obstacles within the barrier's working width. The paper will discuss assumptions to a methodology of numerical models, calculations and automated processing of data to help with assessing the functionality of the devices. The paper will outline the design of the method for selecting optimal road safety devices. This will be based on device selection factors, fieldwork, surveys and simulations. The models and procedures used in the method will help to identify and link different sources of hazard when using road safety devices to tackle a specific event and will help to identify the weaknesses in the safe use of types of road safety devices. The method will take account of the effect of different factors on optimising device selection. They are: types of hazard sources, road class and its parameters, road traffic parameters (volume, structure, speed). The method will be further developed in new research.

Keywords: road restrain system; road safety; numerical models

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1. Introduction

The main goal of the ROSE project (Road Safety Equipment) is to conduct comprehensive tests and analyses of various vehicle restraint systems including those defined under standard PN-EN 1317 and types of supporting structures defined under standard PN-EN 12767 deployed on roads and engineering structures. The work is to include preliminary tests of road safety equipment already in operation, additional site tests for selected crash tests, extended numerical tests and comprehensive analyses to help formulate road safety equipment suggestions and recommendations. The main project result is a method for selecting optimal systems to prevent errant vehicles in relation to: the type and severity of the hazard, road class, volume and structure of vehicle streams and traffic conditions (vehicle speeds) on the roads. The project aims to use and further develop the most modern numerical simulations of crash tests. Figure 1 shows the diagram of project delivery.

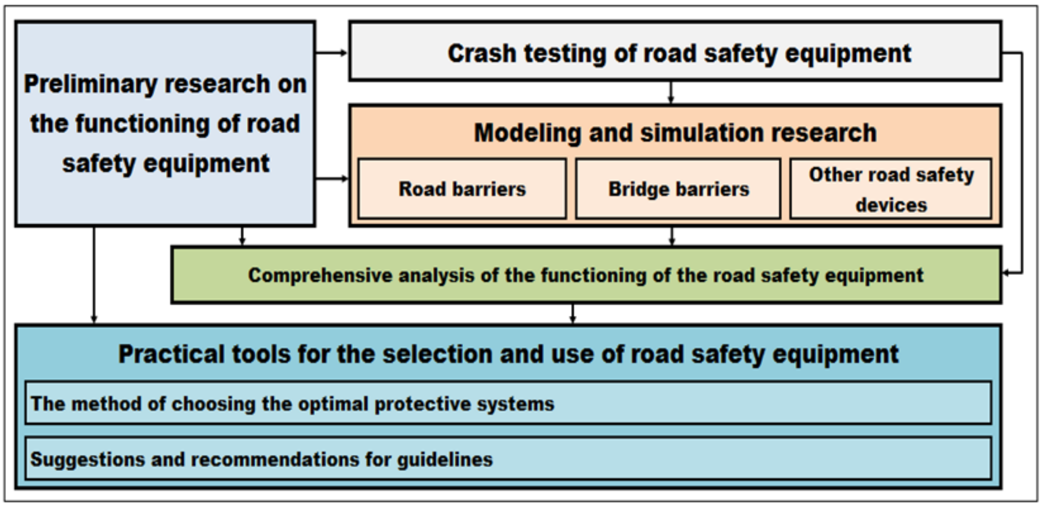

Fig. 1 The diagram of project delivery

As well as adopting the main goal, the project includes specific objectives which are as follows:
- identify hazards and sources of hazards which are the result of a lack of road safety equipment or its poor application and identify wrong design, construction, build and operation of road safety equipment,
- identify the effect of road safety barriers, their design features, additional elements, type of road and barrier location on the road and road and traffic conditions and the effects of wrong safety barrier design, construction, build and operation on their functionality and road safety,
- identify the effect of road bridge parapets, their design features, presence of kerbs on bridges and road and traffic conditions and the effects of wrong safety barrier design, construction and operation on their functionality and road safety,
- identify the effect of other road safety equipment (supporting structures, energy absorption structures, barrier terminals, transitions between barriers of different types) and road and traffic conditions and the effect of wrong safety barrier design, construction and operation on their functionality and road safety,
- develop a classification of road safety equipment depending on the type of equipment, its function and road and traffic conditions by conducting comprehensive and multi-layer analyses of tests and observations and site and numerical tests.

2. Description of the current state of knowledge on the area covered by the project.

As we can see from a literature review, research tends to focus on understanding the effects of selected road parameters (road width, type and width of shoulder, roadside trees and signs), the effect of road structures (bridges, culverts, road signs), roadside obstacles (trees, utility poles) and road safety equipment (safety barriers and guardrails) on the risk of accidents involving errant vehicles. The results of the work were used to model and simulate the effects of different road geometry and traffic parameters on the frequency and consequences of the accidents. Models were used to develop a set of preventative measures and it was demonstrated that accident frequency can be significantly reduced by widening traffic lanes and shoulders, widening central reservations, widening roads on approaches to bridges, moving or removing hazardous roadside objects, reducing slope and ditch gradients, using road safety equipment including safety barriers and other restraint systems, Lee and Mannering (1999). More recent studies focussed on “forgiving” roads with obstacle-free roadside zones. The results of on-site tests, mathematical modelling and computer simulations were used to define recommended widths of obstacle-free zones and the distance from the road and height of safety barriers, Jamieson et al. (2011). Studies often aim to understand the hazards of roadside trees, poor utility pole or road sign design and safety barriers that have been poorly designed or built. The results of this work have been used to develop guidelines and good practices, Holdridge et al. (2005). Poland has had very little research on the effects of hazards and sources of hazards on the likelihood or errant vehicles or the effectiveness of road safety equipment, Budzynski et al. (2016).

Experimental studies on road safety were first conducted in the US in the early 1950s. Today’s experimental crash tests are prepared and conducted under strict procedures set out in the standards, EN 1317 (2010). With high costs of field tests, new research methods were investigated. The new era of research on developing and analysing road safety equipment goes back to the introduction of computer mechanics. First used in the 1960s for military purposes, numerical simulations were used as analytical tools. They were first used for civilian applications in the late 1980s with computer crash simulations. This was supported by the commercial version of the programme LS-DYNA, Hallquist (2007). Simulations of crash tests can also be done in the PAM-CRASH or ABAQUS EXPLICIT programmes. The literature on numerical research on different types of crashes with road safety equipment is very extensive (e.g. Ren and Vesenjak (2005), Borovinsek et al. (2007), Kreja et al. (2000)). Vasenjak et al. (2007) have conducted detailed numerical modelling and simulations of crash tests that are required for containment level H1 under the standard EN 1317. The works, Nycz (2015), Klasztorny et al. (2014) presents numerical modelling and simulation of non-modified (straight line barrier) and modified (curved barrier) crash tests, type TB11 and TB32.

3. Overview of international guidelines

Following an analysis of guidelines and standards from nearly forty countries, similarities and differences between the countries were identified. Some countries developed their own guidelines while others have adapted existing solutions to varying degrees (Poland’s guidelines are an example because they are based on German guidelines) La Torre (2014). Standard EN1317 is Europe’s VRS test standard (vehicle restraint system), while the US follows the NCHRP350 (1992) and MASH (2009). American countries have adopted US standards, central Europe uses German standards and northern and western Europe countries have developed their own rules. Despite that, the guidelines have a number of shared solutions such as decision-making processes, tables or charts. The parameters that determine the type of restraints to be used are divided into thematic groups. Two main categories are distinguished based on the theory of risk: probability and consequences. The probability category includes factors which, if present in a road cross-section, increase the probability of an event. The consequences include factors that increase the severity and consequences of an accident. The charts in Fig. 2 – Fig. 6 show the percentage distribution of factors that determine the use of safety barriers in the particular countries. The percentages represent the number of countries that consider a specific parameter when designing and installing safety barriers Budzynski and Antoniuk. (2017).

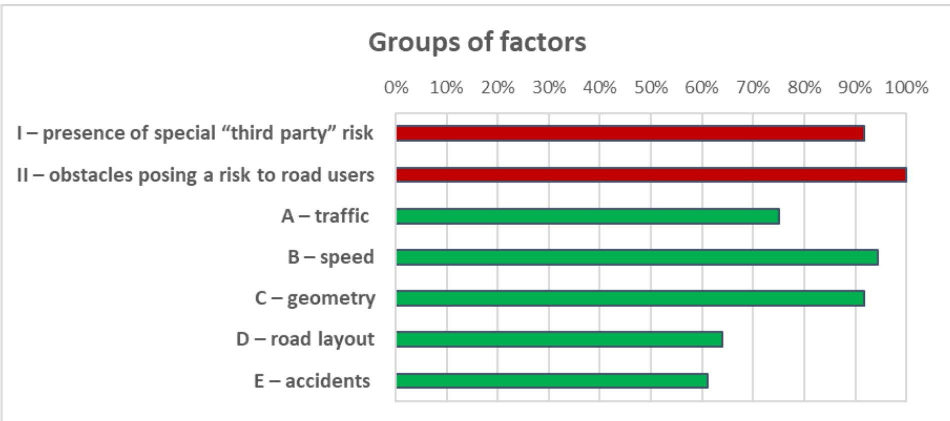

Fig. 2 Groups of factors considered when designing safety barriers based on international guidelines

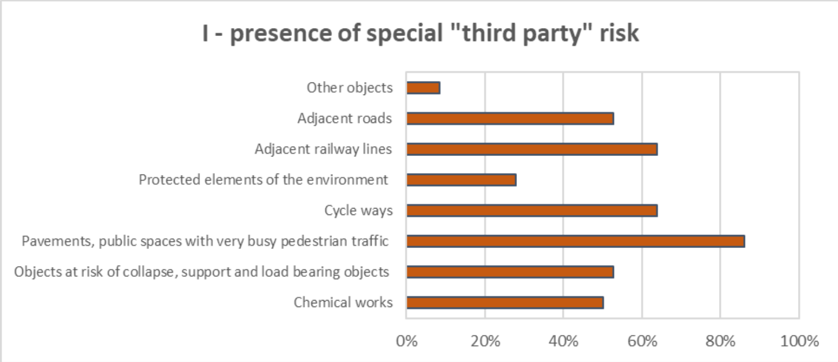

Fig. 3 Groups of factors that pose a hazard to third parties

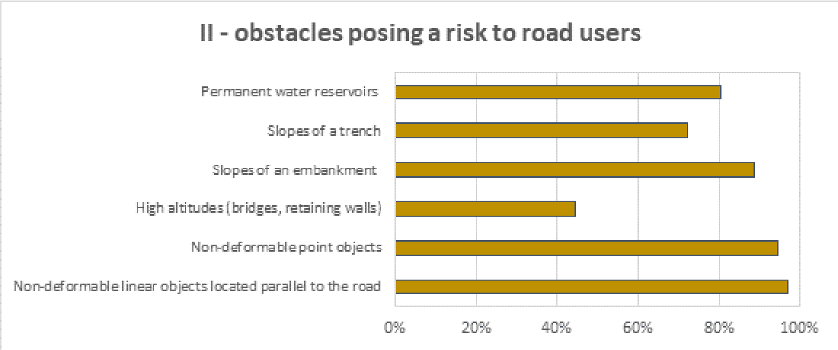

Fig. 4 Groups of factors that pose a hazard to vehicles

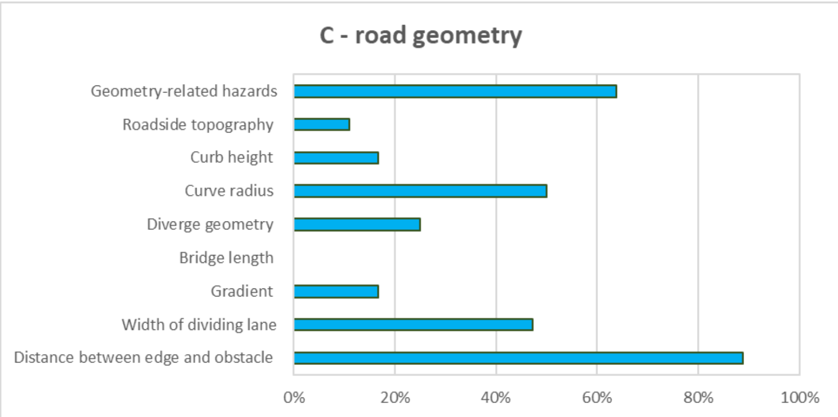

Fig. 5 Traffic conditions for which safety barriers are designed based on international guidelines

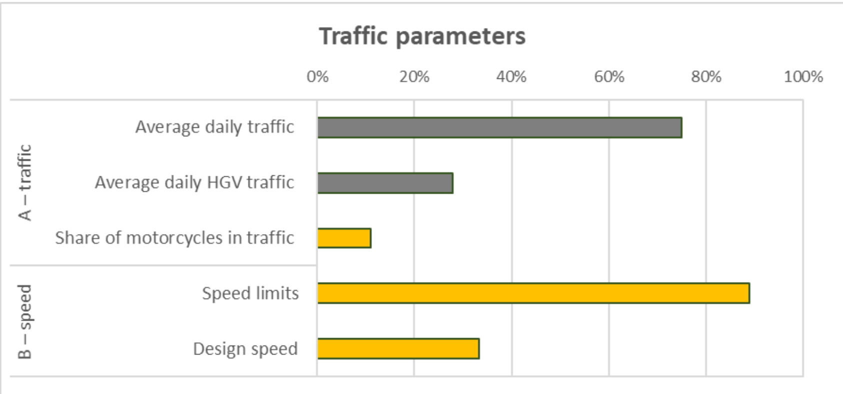

Fig. 6 Geometric conditions for which safety barriers are designed based on international guidelines

Groups of factors can be identified for how frequently they are used in the analysed guidelines. This can further be used when drafting new guidelines for road restraints system design and application in Poland.

4. Identifying the problems

Identifying hazards and sources of hazards caused by a lack of or faulty road safety equipment and identifying poor design, construction, build and operation of road safety equipment is key to understanding the needs for road infrastructure management tools to stop out-of-control vehicles or mitigate the consequences. To meet the needs of this extended examination, field tests, observations and surveys had to be conducted involving road authorities, designers, road safety auditors and maintenance services. By identifying the effects of the types of restraint systems, their construction, additional elements, type of road and safety barrier location on a road or engineering structure and road and traffic conditions on how functional and safe they are, proposals for new guidelines could be formulated.

4.1. Poland's current guidelines

Safety barriers (as the basic devices of active road safety) should be linked to the risk of road safety and roadside hazards. Good design depends on the reliability of vehicle speed determination. Hazards should be removed, moved, or minimised through engineering work other than safety barriers. Road safety equipment cannot be treated as an element of traffic layout design at the last stage of the design when safe solutions can no longer be accommodated due to a lack of space. Sadly, this is frequent practice in Poland's design processes.
Prior to the project, using the existing research, publications, conclusions of scientific conferences and direct contacts a set of deficiencies and needs were identified reported by the managers of the National Road Administration, designers and road authorities. These are mainly:

- lack of recognition, knowledge and information about: the frequency and consequences of events related to vehicles running off the road and hitting road safety equipment under different road and traffic conditions, impact of incorrect solutions of road safety equipment, resulting from ignorance or poor management, impact of selected factors (class, and road geometry, functionality, traffic conditions) on the functioning of road safety equipment and behaviour of the vehicle when colliding with road safety equipment,
- lack of methods to analyse and evaluate the impact of various types of road safety equipment under different road and traffic conditions, select optimal road safety equipment for a variety of road and traffic conditions.

Selected general problems involved in the current guidelines, GDDKiA (2010):

- new issues: lack of new containment levels L1, L2, L3, L4a, L4b, lack of parameters – vehicle intrusion VI and dynamic deflection D, need to update rules for designating areas at risk,
- lack of rules for how to use and select parameters for equipment other than safety barriers: crash cushions, supporting structures, anti-glare screens, safety barrier terminals, transitions and temporary safety barriers, pedestrian guardrails, motorcyclist restraints, culvert covers, etc.,
- problem of safety barriers installed before the PN EN-1317 standard,
- roadworks safety,
- lack of safety zone dimensions.

4.2. Studies of road safety equipment and roadsides as they are today

A study was conducted (based on a survey of designers, traffic managers, road safety auditors and road safety inspectors) to identify the main groups of causes leading to problems in the area of planning and designing road safety equipment:

- differences between the design expectations and the actual laws and technical standards,
- differences between design requirements which are the consequence of laws and technical standards and the market offer of road safety equipment in terms of how they fit the design: the functions, utility parameters and construction solutions,
- conceptual differences and errors caused by the human factor during design, approval, delivery of the design (construction) and how it is inspected.

Road user safety should be seen in a broader picture as a "safe system of procedures and interrelations" with consistent guidelines to guarantee at whatever the decision-making level that road safety equipment will be properly and safely used, designed, applied, built and inspected.
The project included research on the state of road safety in relation the roadside, an element which is vital for ensuring proper dimensions of safety zones. Between 2013-2015 there were 16,500 accidents involving the roadside (11% of all accidents in this period). The consequences were 20,700 injuries (16%), of which 6,400 people were seriously injured (16.4%) and 2,100 people were killed (24%). The work was based on accident

databases, road elements and fieldwork on test sections. Key to understanding roadside hazards is analysing road safety inspection reports and road designs for their road safety impacts. A preliminary evaluation of the reports has helped to identify the main road safety problems on national roads involving roadsides:

- trees close to the edge of the road (up to 3 metres away from the edge of the carriageway the risk is the highest, especially in the area of curves in horizontal alignment, junctions and exits),
- other green restricting visibility,
- elements of infrastructure which are unyielding,
- supports of civil engineering objects too close to the edge of the road, unsecured,
- drainage – vertical concrete front walls of culverts,
- steep embankments,
- poor technical condition of shoulders,
- inadequately terminated, too short, wrong operating width and damaged road barriers,
- lack of safety barriers or other vehicle restraint systems in places where having these systems has been proved to reduce accident severity,
- safety barriers are designed too late in the design process which means that they must "fit in" with what has already been planned; it is important to analyse road safety equipment requirements as early on as possible.

5. Crash tests conducted under the project

This task included an extensive study of the literature. Experts and representatives of the General Directorate for National Roads and Motorways were consulted at length. A detailed review was conducted of previous safety barrier fieldwork to create a crash test database. An analysis of generally available reports and reports obtained by the authors helped to identify a set of problems which were investigated poorly or not at all. The following crash tests were performed (fig. 7):

- TB32 crash test, conducted in accordance with standard PN EN-1317:2010 for a road wire rope barrier for a section of a barrier installed on a curve with a radius of 400 metres. (Deviation from the standard is the barrier on a horizontal curve, the rest follows the rules of the standard). In addition, a second crash was conducted in the same place. Justification: Little is known about barrier behaviour on horizontal curves, in particular when the barrier is hit on the inner (convex) edge of road on a horizontal curve. Of particular importance for identifying the potential width of the obstacle-free zone behind the barrier.
- TB32 crash test, conducted in accordance with standard PN EN-1317:2010 for a road steel barrier for a section of a barrier installed on a curve with a radius of 400 metres. (Deviation from the standard is the barrier on a horizontal curve, the rest follows the rules of the standard). Justification: Little is known about barrier behaviour on horizontal curves, in particular when the barrier is hit on the inner (convex) edge of road on a horizontal curve. Of particular importance for identifying the potential width of the obstacle-free zone behind the barrier.
- TB11 crash test, conducted in accordance with standard PN EN-1317:2010 for a road steel bridge parapet (low) mounted on a concrete plate with a 14 cm high kerb. Justification: Need to better understand vehicle behaviour upon hitting the kerb and parapet with special emphasis on the ASI parameter. Lack of sufficient baseline materials for numerical tests.
- TB51 crash test, conducted in accordance with standard PN EN-1317:2010 for a road steel bridge parapet (low) mounted on a concrete plate with a 14 cm high kerb. Justification: Need to better understand vehicle behaviour upon hitting the kerb and parapet with special emphasis on the ASI parameter. Lack of sufficient baseline materials for numerical tests.
- TB32 crash test conducted in accordance with standard PN EN-1317:2010 for the connection between a road wire rope barrier with a steel barrier. Justification: Need to better understand system behaviour and the effect on the vehicle for a frequently used connection in Poland. Lack of sufficient baseline materials for numerical tests.
- TB51 crash test, conducted in accordance with standard PN EN-1317:2010 for a steel barrier and lighting column placed within the barrier's working width. A steel barrier H2-W4-A, column class HE100. Justification: A frequent occurrence in Poland to have objects placed within the barrier's working width (lighting columns, gantries, etc.). Poor understanding of how the system works and the consequences of a crash, in particular involving an errant vehicle.

Fig. 7. Sample photos from crash tests

6. Modelling and simulation tests of road safety barriers

The first stage of the work was designed to select a numerical tool and develop a method for numerical simulation of crash tests. Programmes based on the Finite Element Method and designed for solving major dynamic problems in the domain of time were analysed and tested. The decision was to use the Ls-Dyna system, one of the most frequently used crash test programmes by the international community. Available for a fee or for free, it includes MES models of vehicles in the Ls-Dyna format for direct application in this project's work.
Under the Ls-Dyna license calculations can be made in parallel on 2000 processing cores. It was decided that the main computations should be conducted on Tryton, a super computer owned by the TASK IT Centre, Gdansk University of Technology. The work began with conducting numerical simulations of a vehicle hitting a road safety barrier for two types of steel barriers (different manufacturers). In both cases new computational models were built in the Ls-Dyna's Finite Element Method (FEM) environment using the available product documentation. Vehicle numerical models (which are not covered by the work) were sourced from generally available open source on-line libraries. Numerical validation tests were conducted on the vehicle models to correct errors and improve model parameters to ensure that they are better prepared for safety barrier tests. Simulations of the basic crash cases (standard TB11 test) were validated against manufacturer declared parameters (ASI, THIV and others as available). To ensure that numerical simulations are reliable, numerical models must be validated in reference to actual site tests. Table 1 shows the parameters along with those from numerical simulations. In the case of the second barrier, validation included a comprehensive analysis of material parameters and an assessment of numerical techniques that are designed to represent the processes that occur during a crash as accurately as possible. Changes in parameters were considered such as: ground modelling, steel stress-deformation curve and its viscoplasticity parameters. To ensure that the numerical models are correct, they must be validated using test site data, a pre-condition for further work such as a comprehensive parametric analysis for the angle, speed and place of vehicle crash, etc.

As work on the road safety barriers continued, a virtual model of a bridge barrier in the Ls-PrePost environment (pre-processor of Ls-Dyna) was developed. It is a class B parapet with working width W2 and containment class H2. For the purposes of the TB11 standard crash test according to EN1317-2010, a FEM model of a Geo Metro vehicle was obtained. First, the control cards were checked in the model's source file. Pilot numerical tests were conducted to assess whether the vehicle model correctly represents simple physical states such as representing the specific weight or the straight line drive test. Initial numerical tests of different vehicle models available on-line showed that they were designed for different research objectives and included a number of errors. Vehicle models had to be corrected or improved to meet the needs of crash analyses. At the same time the shear correction factor SHRF was studied for its effect on the results. Other work focussed on selecting a method for checking parasite forms (non-physical forms of deformation but not with zero deformations) in finite elements with reduced integration (RI). A study of the literature and own experience with programmes, Chroscielewski et al. (2004) helped to select a method which introduces extra rigidness for checking the formation of parasite forms (IHQ=4) with parameter QM=0.03. Following the analyses, necessary corrections were made to the vehicle model's file source. The experience is currently used in all of the project's numerical simulations.

Along with passenger car tests, the TB51 test simulations were conducted. For the purposes of the test two FEM coach models were obtained. The first is a generally available FEM model. However, the discretisation of its body and in particular of its front bumper and door produces an overly simplified representation. Some of the results from the model are shown in the work, Wilde et al. (2016). A more accurate coach model was obtained, courtesy of the NPRA (Norwegian Public Road Administration). Just as with the Geo Metro model, initial simulations were conducted and control cards were checked. The results of the vehicle's body deformation suggested the presence of zero-energy parasite forms, i.e. non-physical shapes of the deformed finite elements. The definition of finite elements was corrected and selected elements were replaced with full integration (FI). The results were satisfactory. The model was also used to study the discretisation of barrier connections. Some of the variants tested showed physically wrong disproportions of the grid's finite elements deformation. Appropriate corrections were made to eliminate the errors. This task included the development of numerical models and numerical simulations of crash tests involving road safety devices, other than safety barriers. The work involved numerical analyses of crash tests with a supporting structure within working width and numerical analyses of crash tests involving barrier terminals. Supporting structures within working width are considered bad practice in terms of the design and construction with a negative impact on the crash. Car crashes into barrier terminals to assess the performance are not required under PN-EN 1317:2010. In accordance with the test schedule a numerical model was built of a roadside structure i.e. the supporting structure of a road sign. The pole and arm of the supporting structure are made from round rods with a complete cross-section and metal plates at pole base. To ensure that the contact is properly represented, a fragment of the pole that may come into contact with the barrier or vehicle was enriched with a non-structural (non-material) coating to help with describing the simulated contact. The structure's model consists of 15 244 nodes and 18 003 finite elements.

The model was used to assess the effect of placing the supporting structure within barrier working width, which is wrong in terms of the design and construction. Sadly, this is a very frequent occurrence on the roads. A complete numerical simulation was conducted of the coach hitting the bridge barrier (containment level H2, working width W2) where the grid supporting structure is placed (e.g. to support information boards) above the road zone. The crash parameters were consistent with the TB51 test (a coach weighing 13 t hits a barrier at 70 km/h at angle 20°). The results were compared with those from an analogous test without the supporting structure within working width. The model included control of zero-energy forms in elements with reduced integration, using the stiffness form of type 2 technique, Flanagan-Belytschko. The QH (hourglass coefficient) was 0.03. The correctness of the numerical simulation was confirmed using the energy variability analysis for dynamic processes. The energy of parasite forms stays at a very low level. The results of numerical analyses show that the supporting structure has a major contribution to the crash causing significant and permanent deformations of the coach and barrier. Permanent deformations of posts when the supporting structure is within working width are significantly weaker when the crash involves the barrier only. During the crash the roof of the coach comes into undesired direct contact with the pole of the supporting structure damaging the back of the coach's passenger cabin and permanently displacing the upper part of the pole. The analyses are published in the journal, Klasztorny et al. (2016).

The next issue under consideration was the effect of the supporting structure within the working width of a road safety barrier during the TB11 test (vehicle weight 900 kg, speed 100 km/h, angle of impact 20°). Special attention was paid to indicators ASI, THIV and PHD which determine the effect of the impact on people inside the vehicle. The analysed system consists of a Geo Metro vehicle, safety barrier and supporting structure. In the first stage the model without a supporting structure was validated against the results of a real crash test. The achieved parameter, acceleration times and indicator consistency was very good. Next, a supporting structure was added to the validated numerical model. Three cases were analysed of the supporting structure versus the point of vehicle impact into the safety barrier (marked as "c'): at a distance of 3, 4 and 5 m from crash point. The table 1 shows representative results for the simulations. The results show a very negative effect of the supporting structure being within the barrier's working width which may have catastrophic consequences for vehicle occupants. The parameters, including the most important indicator for vehicle occupant safety ASI, exceed significantly the limits set out in the crash intensity standard A (ASI ≤ 1.0; THIV ≤ 33 km/h; PHD ≤ 20 g).

Tab. 1. Values of indicators depending on the distance between the supporting structure and the place of impact (distance c)

"c" [m]	ASI [-]	THIV [km/h]	PHD [g]
3	2,45	47,0	31,8
4	2,60	28,3	47,0
5	2,22	25,9	32,7

In addition, numerical simulations of crash tests were conducted involving barrier terminals installed in the ground. Simulation parameters were consistent with the requirements for the TB11 test (vehicle weight 900 kg, speed 100 km/h, angle of impact 20°). In the first stage the TB11 test model was validated against the results of a real crash tests. The achieved consistency was very good on quality and quantity. Next, the vehicle was transformed so that it would hit barrier terminals at the beginning and end. Five crash points were analysed – 3 hits in the beginning terminal (beginning A, middle B and end of terminal C), 2 hits in the ending barrier terminals (beginning D and middle of terminal E). Table 3 shows ASI, THIV and PHD for different crash points. Please note that when the ending terminals are hit (D and E), the rates are lower than when hitting the beginning terminal. When the crash involves the point in the middle of the length of the beginning inclined barrier section, the vehicle capsizes.

Tab. 2. Values of indicators depending on the place of vehicle crash into barrier terminal

Place of impact	ASI [-]	THIV [km/h]	PHD [g]
A	0.55	18.4	12.4
B	1.53	23.4	24.6
C	0.79	25.1	18.7
D	0.89	22.6	14.9
E	0.62	15.4	8.8

7. Summary

The main goal of the ROSE project (Road Safety Equipment) is to conduct comprehensive tests and analyses of various vehicle restraint systems including those defined under standard PN-EN 1317 and types of supporting structures defined under standard PN-EN 12767 deployed on roads and engineering structures. A study was conducted (based on a survey of designers, traffic managers, road safety auditors and road safety inspectors) to identify the main groups of causes leading to problems in the area of planning and designing road safety equipment. The project included research on the state of road safety in relation the roadside, an element which is vital for ensuring proper dimensions of safety zones. Between 2013-2015 there were 16,500 accidents involving the roadside (11% of all accidents in this period). The consequences were 20,700 injuries (16%), of which 6,400 people were seriously injured (16.4%) and 2,100 people were killed (24%). A detailed review was conducted of previous safety barrier fieldwork to create a crash test database.

An analysis of generally available reports and reports obtained by the authors helped to identify a set of problems which were investigated poorly or not at all. The nine crash tests were performed: TB32 for road wire rope barrier on a curve (and second crash), TB32 road steel barrier on a curve (and second crash), with a radius of 400 metres, TB11 for a road steel bridge parapet (and second crash), TB51 for a road steel bridge parapet, TB32 for the connection between a road wire rope barrier with a steel barrier, TB51 for a steel barrier and lighting column placed within the barrier's working width.

The first stage of the modelling and simulation tests of road safety barriers was designed to select a numerical tool and develop a method for numerical simulation of crash tests. Programmes based on the Finite Element Method and designed for solving major dynamic problems in the domain of time were analysed and tested. The decision was to use the Ls-Dyna system, one of the most frequently used crash test programmes by the international community. Available for a fee or for free, it includes MES models of vehicles in the Ls-Dyna format for direct application in this project's work. The correctly validated model can be used for calculating the type of parametric study, accurate verification of generally available vehicle models is needed.

Acknowledgements

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8. References

Borovinsek M., Vesenjak M., Ulbin M., Ren Z., 2007. Simulation of crash test for high containment levels of road safety barriers, Engineering Failure Analysis 14.

Budzynski M., Jamroz K., Jelinski Ł., Antoniuk M.., 2016. Why are trees still such a major hazard to drivers in Poland?, W: 6th Transport Research Arena (TRA), ELSEVIER SCIENCE BV.

Budzynski M., Antoniuk M., 2017. The guidelines and principles for planning and design of road restraint systems. MATEC Web of Conferences. Volume 122 (2017). XI International Road Safety Seminar GAMBIT 2016, Poland.
Chroscielewski J., Makowski J., Pietraszkiewicz W., 2004. *Statics and dynamics of multilayer coatings. Nonlinear Theory and Finite Element Method, Library of Applied Mechanics* PAN IPPT, Warsaw.
EN 1317 – Part 1-3 : 2010. Suite of Performance Standards for the design, manufacture & testing of vehicle restraint systems (VRS) to a common European Standard.
GDDKiA, 2010. Guidelines for the use of road safety barriers on national roads, Warsaw.
Hallquist J. O., 2007. LS-DYNA Keyword User's Manual, Livermore Sofware Technology Corporation, Livermore, CA, USA.
Holdridge J. M., Shankar V. N., Ulfarsson G. F., 2005. The crash severity impacts of fixed roadside objects. Journal of Safety Research 36.
Jamieson N.J., Waibl G., Davies R., 2011. Use of roadside barriers versus clear zones. NZ Transport Agency research report 517, Wellington, New Zealand.
Klasztorny M., Niezgoda T., Romanowski R., Nycz D., Rudnik D., Zielonka K., 2014. Overlay on the barrier barrier guide, Patent application P.409756.
Klasztorny M., Nycz D. B., Szurgott P., 2016. Modelling and simulation of crash tests of N2-W4-A category safety road barrier in horizontal concave arc, International Journal of Crashworthiness.
Kreja I., Mikołajków L., Wekezer J., 2000. Computer simulation of vehicle collisions with road safety devices, Road construction, Vol. 8.
La Torre F., 2014 "SAVeRS Selection of Appropriate Vehicle Restraint Systems," 2014, no. February.
Lee J., Mannering F., 1999. Analysis of roadside accident frequency and severity and roadside safety management. Research Report T9903, Task 97; US DOT, FHWA, Washington.
Manual for Assessing Safety Hardware, 2009. American Association of State Highway and Transportation Officials.
NCHRP 350, 1992 Recommended Procedures for the Safety Performance Evaluation of Highway Features. Transportation Research Board
Nycz D., Modeling and numerical testing of N2-W4-A barrier crash tests on road bends, 2015. PhD thesis, Military University of Technology, Warsaw.
Ren Z., Vesenjak M., 2005. Computational and experimental crash analysis of the road safety barrier, Engineering Failure Analysis 12.
Vesenjak M., Borovinšek M., Ren Z., 2007. Computational simulations of road safety barriers using LS-DYNA, 6. LS-DYNA Anwenderforum, CD Proc. pp. 1-8, DYNAmore, GmbH, Frankenthal.
Wilde K., Jamroz K., Bruski D., Burzyński S., Chroscielewski J., Witkowski W., 2016. Numerical study of bus collision in barrier system and truss support structure, JCEEA, t. XXXIII, z. 63 (1/I/16).