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Road Restraint Systems as a Basis for Roadside Safety Improvement

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Abstract. Roadside-related crashes occur when vehicles run off the road. The majority of the crashes have severe outcomes, especially when an object is hit (tree, pole, supports, front wall of a culvert, barrier). These accidents represent app. 19% of all of Poland's road deaths. Roadside crashes involve: hitting a tree, hitting a barrier, hitting a sign or utility pole, vehicle roll-over on the roadside, vehicle roll-over on a slope and vehicle roll-over into a ditch. Understanding the effects of roadside factors on road safety requires in-depth research. The problem was partly addressed at the WMCAUS conference in 2017 [1]. 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. It is also important to identify errors in the design, structure, construction and operation of road safety devices. Studying such an extended scope of the problem required fieldwork. Site tests had to be conducted such as hitting a wire rope barrier and a steel barrier on curve (test TB32), light and heavy vehicles hitting a bridge parapet (tests TB11 and TB51), hitting a transition between a steel and wire rope barrier (TB32) and crashes into a lighting column placed within the barrier's working width. In addition, the project includes numerical tests validated on the basis of site tests. This helps to assess the behaviour of road restraint systems when selected parameters are changed. The work is part of the RID Programme (Development of Road Innovation) and the RoSE project (Road Safety Equipment). In the article the authors present the effects of building a road restraint system database for a selected test site (about 3,000 km of Poland's national roads). An outline of new road restraint system 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. Once complete, the research will offer tools to help with the implementation of road restraint systems. The tools will ensure that road infrastructure is safer and that the most common mistakes are eliminated.

1. Introduction

Roadside-related crashes occur when vehicles run off the road. The majority of the crashes have severe outcomes, especially when an object is hit (tree, pole, supports, front wall of a culvert, barrier). These accidents represent app. 19% of all of Poland's road deaths. Roadside crashes involve (based on SEWIK, a police database): hitting a tree (the main hazard), hitting a barrier, hitting a sign or utility pole, vehicle roll-over on the roadside, vehicle roll-over on a slope and vehicle roll-over into a ditch. The main consequence of a roadside hazard is not the likelihood of an accident itself but of its severity [2].

Poland's roadside accident severity is primarily the result of poor design or operation of road infrastructure. This comes as a consequence of a lack of regulations or poorly defined regulations and failure to comply with road safety standards [3]. Safety barriers are also part of the roadside. While they protect motorists from hitting an obstacle or stop vehicles from leaving the road in the case of steep embankments, they are obstacles themselves, which if poorly designed and built, may pose a serious risk [4] [5]. Safety barriers are part of road safety devices.

Road safety devices can be divided into two groups. Active devices are designed to handle the impact of out-of-control vehicles, including collisions and crashes. They are specifically designed to minimise the consequences of such events, especially those involving people (injury or death). Passive devices do not come into direct contact with vehicles involved in a crash or accident and are only used to organise and control road traffic, prevent disruptions to traffic and inform motorists and other road users in advance about safety risks or traffic delays. Safety barriers are active road safety devices and are used if the consequences of a crash or accident were greater than those caused by crashing into a barrier (e.g. hitting a tree). To ensure that barriers are effective, they must be designed to successfully handle vehicle impact because their main objective is to protect road users (and roadside users) from fatal injury. Further in the article safety barriers will be referred to as road restraint systems.

In-depth research is required to understand how roadside factors affect road safety. Key to this is analysing and evaluating the need for road restraint systems and the selection of specific solutions. This is an area studied under the RID Programme (Development of Road Innovation) in the Road Safety Equipment project called RoSE. It aims to identify the selection criteria and conduct site tests and crash and simulation tests. The results will feed into a set of proposed methods for how to select road restraint systems. Sections of national roads are used to build models to describe the effects of selected road and traffic factors, including roadside factors, on road safety.

2. Knowledge

A review of research on the effects of roadside on road safety shows that it 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 [6] [7] [8]. 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 [9] [10].

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 [11] [12]. 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 [13] [14]. While the circumstances and hazards are different, all countries share the same problem of hazardous roadsides. Effective and efficient solutions should be sought with object life cycle as an important factor [15] [16].

One of the most important projects implemented in Europe was RISER [17] (Roadside Infrastructure for Safer European Roads). The project was designed to determine the behaviour of drivers (in adjusting speed) to the conditions encountered. A correlation was established between the occurrence of the central reservation and the type of barrier and also the dependence of the vehicle's road position on the obstacle type. An equally important project is Saver which looks at the use of road safety equipment across Europe and ways to improve road safety, including roadside safety [18].

Poland has had very little research on the effects of hazards and sources of hazards on the likelihood of errant vehicles or the effectiveness of road safety equipment [19]. There has been more work on the other factors contributing to road accidents such as speed [20], traffic organisation [21] or vulnerable road users [22]. First launched a few years ago, Poland has been implementing tools for road safety management [23] which includes tools for roadside safety management.

3. Methodology

The main goal of the ROSE project (Road Safety Equipment) is to conduct comprehensive tests and analyses of various vehicle restraint systems 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 analyses are expected to help draft recommendations on how to select solutions and functional parameters of road restraint systems. Two groups of tools are envisaged providing support for the design, construction and maintenance of road safety equipment. They will include:

- a new method for selecting optimal systems to prevent vehicles from running off the road to take account of the type and severity of hazards, road class, size and structure of traffic and driving conditions (vehicle speeds) on the road,
- new recommendations for the guidelines regarding the construction of road safety devices, design and construction of restraint systems and instructions for services responsible for maintaining vehicle run-off prevention systems for different road and traffic conditions.

The new methods, recommendations and practical tools will be built using Polish, European and worldwide experience and practices. The project's additional objective is to provide the technical input to road safety equipment guidelines. The devices will include safety barriers, crash cushions and passive support structures on the network of national roads. Figure 1 shows a diagram of the project.

3.1. Crash tests

Before selecting crash tests for the purposes of the RoSE project, there was an extensive review of the literature and experts were consulted at length [24], [25]. 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. This was the basis for carrying out nine site tests (figure 2):

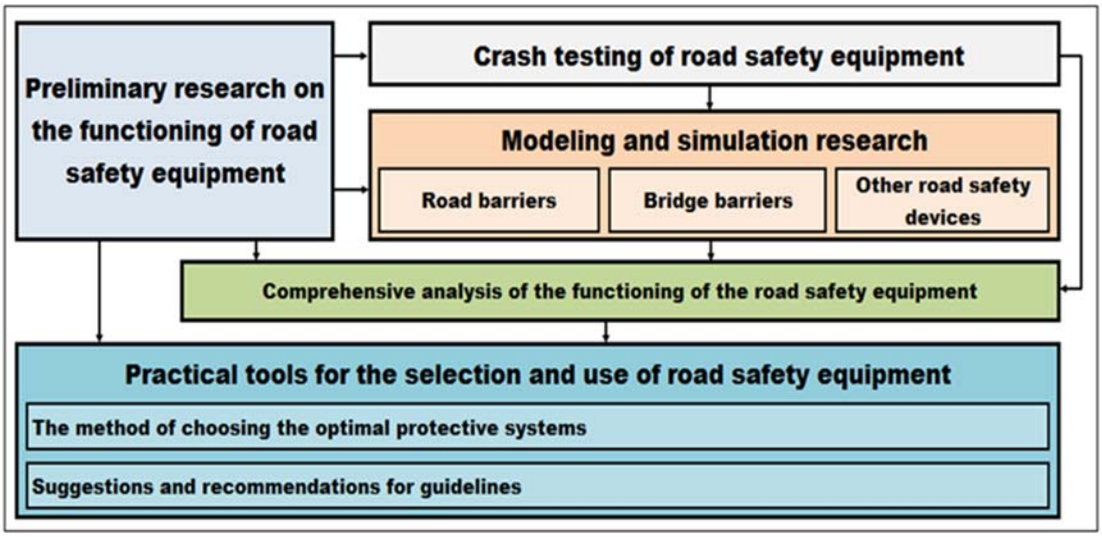
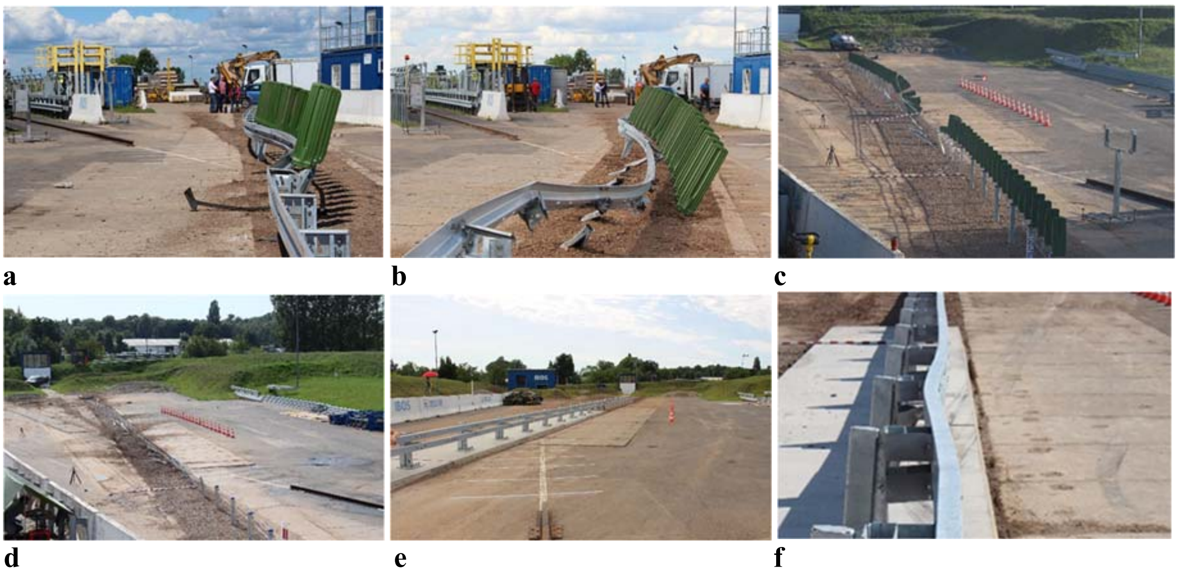


Figure 1. The diagram of project delivery

- 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. 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 (figures 2A and 2B).
- 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. 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 (figures 2C and 2D).
- 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. In addition, a second crash was conducted in the same place. 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 (figures 2E and 2F).
- 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 (figure 2G).
- TB32 crash test conducted in accordance with standard PN EN-1317:2010 for the connection between a road wire rope barrier and 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 (figure 2H).
- 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 (figure 2I).



a **b** **c**

d **e** **f**

Figure 2a) – i). Crash tests conducted in the ROSE project.

3.2. Databases

Understanding how safety barriers change road safety requires in-depth studies such as database exploration and design, conducting numerical tests (based on crash tests) and safety modelling. More than seventy sections of national roads with a total length of about 3000 km across all of Poland's regions are being monitored for road accidents, road parameters and traffic volumes (figure 3).

Region	**Road class [km]**		
	A	**S**	**G, GP**
Podlaskie	0.0	32.4	171.8
Kujawsko-Pomorskie	171.3	0.0	0.0
Pomorskie	73.8	67.4	102.9
Śląskie	37.7	25.2	47.4
Świętokrzyskie	0.0	47.2	3.6
Małopolskie	100.5	15.7	63.2
Lubelskie	0.0	67.9	1.8
Łódzkie	198.5	166.0	0.0
Warmińsko-Mazurskie	0.0	91.7	22.0
Opolskie	87.7	0.0	0.0
Wielkopolskie	104.0	129.3	0.0
Podkarpackie	167.3	0.0	19.4
Zachodniopomorskie	0.0	67.1	8.6
Mazowieckie	43.4	159.0	172.2
Dolnośląskie	216.5	54.2	44.8
Lubuskie	0.0	112.4	0.0
Total:	**1200.9**	**1035.5**	**657.7**
		2894.0	

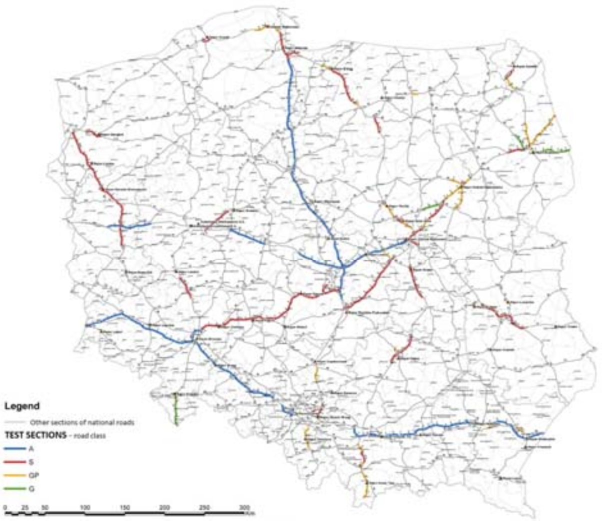


Figure 3. Test site on the network of national roads

The collected data are used to develop models of road safety measures and methods for managing road safety tools. Similarly to the TRL research [26], as part of observation of how road safety devices operate, various road sections were selected according to the devices applied (old type, new type, steel, wire rope, concrete) and traffic and road parameters. An important criterion for the selection of sections was the assessment of individual risk [27] of running into safety barriers or poles. Data were divided into three groups: Road Database – containing information about sections, location, geometry, roadside; Traffic Database – containing data on the volume, type of traffic structure; Accident Database – containing data on accidents, victims, circumstances, types, causes, perpetrators, etc. (figure 4).

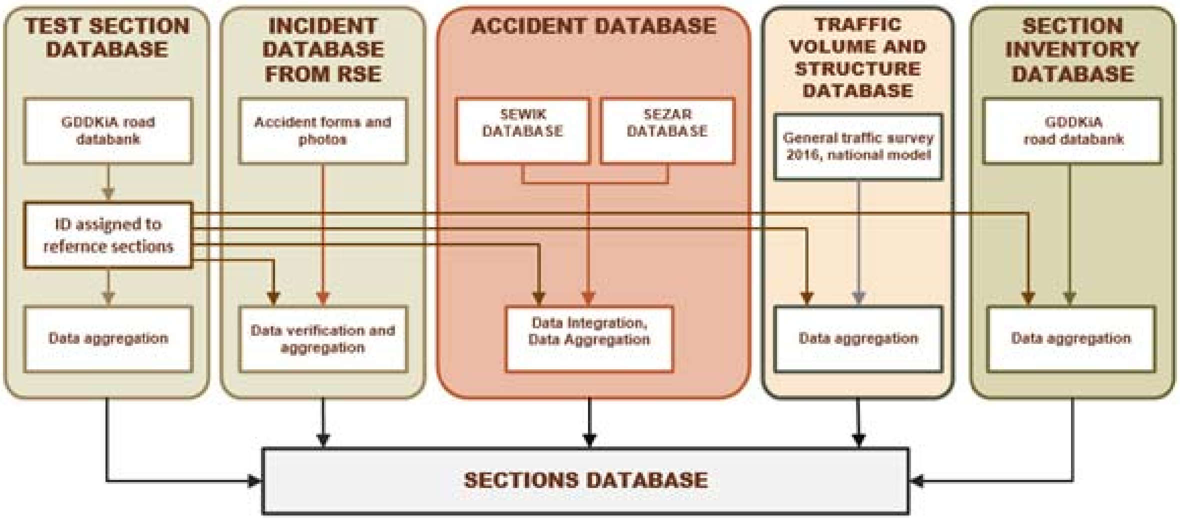


Figure 4. Database diagram

The data collected at these sites includes photographic documentation of accidents that involve running into a road safety device (figure 5). There is photographic evidence assigned to the different road restraint hazards such as cars penetrating barriers, crashing into crash cushions, into objects placed with the barrier's working width and into barrier transitions, poorly compacted soil, etc.

3.3. Data analyses

Using the data on road network and roadside parameters the main run-off-road hazards were identified:

- narrowing of road and roadside which forces vehicles to drive on the opposing traffic lane (head-on collisions),
- reduced visibility at junctions and exits (side impact),
- road signs covered up (road not clear or understood),
- no space for pedestrian traffic and reduced visibility at pedestrian crossings (hitting a pedestrian)
- causing damage to road infrastructure,
- dangerous barrier terminations,
- lack of barriers which if present would reduce the risk of running off the road and, by the same token, accident severity (tall embankments, obstacles),
- dangerous elements of drainage (vertical culvert walls),
- roadside obstacles increasing crash severity (trees, utility poles);

Road accident data analysis helped to assess the individual risk of roadside-related accidents (figure 6). Individual risk in this case is defined as the number of fatality and/or injury accidents in relation to kilometres travelled on that particular road section (billions of vehicle-kilometres per year) – as a measure of the injury and fatality accident rate. A risk map was created which helps to identify the most hazardous road sections. A five degree risk class was adopted with "high risk" and "very high risk" categories suggesting the need for urgent treatments.

Barrier penetration

Crash into cushions

Lighting columns with barrier working width

Barrier transition

Poorly compacted soil

Figure 5. Examples of crashes into road restraint systems (source: GDDKiA)

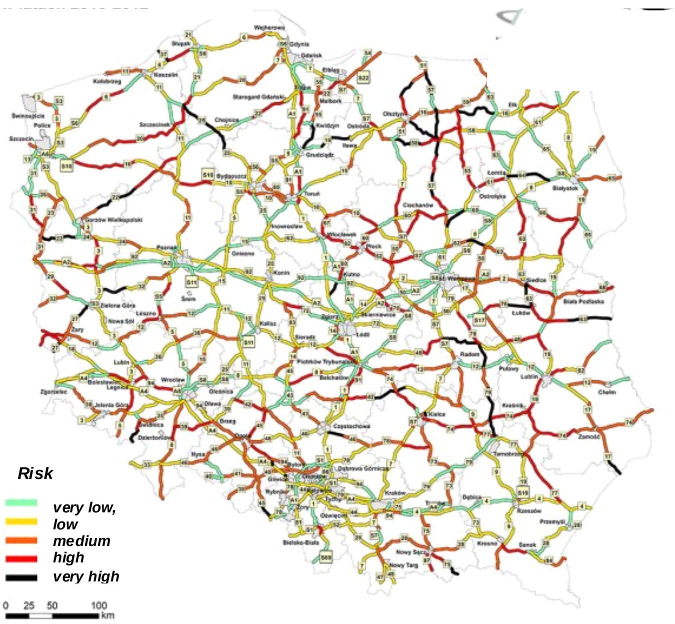


Figure 6. Map of run-off-road risk (2012-2014)

4. Modelling the effects of roadside on road safety

Analyses of models of how roadside elements affect road safety [28] [29] showed that the methodologies and data differ from model to model. Because the models focus on different factors, they each have strengths and weaknesses. A new analytical model was designed as a combination of the different factors and one that will serve as a comprehensive model for Polish conditions. It was assumed that it will describe the effect of the roadside on the number of accidents and their consequences. The design of the model was based on recommendations from analysing other models. The assumptions were the following: the model will be used to calculate risk factors and accident severity, the indicators will depend on the number of vehicle kilometres travelled or traffic volumes, analyses will be based on accident data: striking a tree, hitting a barrier, hitting a utility pole or sign. Additional data will include roadside information and casualty density measures will be used – killed and injured. The results of the study are presented based on the victims density (DA) model for single-carriageway roads of GP class (main road with accelerated traffic) outside a built-up area. The accident density model is described with the following formula (table 1):

$$\mathrm{DA} = \alpha \cdot Q^{\beta_1} \cdot e^{(\mathrm{B}^{\beta_2} + S^{\beta_3} + T_1^{\beta_4} + T_2^{\beta_5} + T_3^{\beta_6} + C^{\beta_7} + P_1^{\beta_8} + P_2^{\beta_9} + P_3^{\beta_{10}})} \qquad (1)$$

where:

DA	expected number of accidents per kilometres of road
α	adjustment coefficient
Q	annual average daily traffic (AADT)
βj (1,2,…,n)	calculation coefficients
B, S, T_1, T_2, T_3 C, P_1, P_2, P_3	factors related to the risk of an accident

In the case of the DA victims' density model, the determination coefficient is 0.72. The factors with the strongest effect on the model had to do with barriers, number of trees along the carriageway (up to 3.5 and more than 3.5 m from the edge), number of barriers and road class. The study showed that accident density goes down as the number of barriers and hard shoulders goes up. When all the other parameters are averaged and the effects of traffic, AADT, are included, DA shows a clear increase for more than a 60% share of sections with roadside trees that are less than 3.5 m away from the road edge and no barriers are present. Where safety barriers are present, DA drops significantly for sections with roadside trees more than 3.5 m away from road edge and embankments. As the work continues, it will study a greater level of detail: the height and gradient of slopes, presence of obstacles, share of heavy goods vehicles, type of safety barriers, roadway width, different cross-sections (single and dual carriageways, 2+1 cross-section).

Table 1. Parameter estimates of the crash prediction model of Eq. (1)

Parameter	Coefficients	Value
Adjustment	α	0.01
Traffic volume Q	β_1	0.79
% of barriers B	β_2	-2.03
% of embankments S	β_3	1.25
% of trees to 3.5m T_1	β_4	2.87
% of trees above 3.5m T_2	β_5	-0.58
% of forests T_3	β_6	-0.38
Road class C	β_7	-2.90
% of shoulders above 1.5 m	β_8	-0.47
% of shoulders to 1.5 m P_2	β_9	-0.10
% of soft shoulders P_3	β_{10}	0.38

5. Conclusions

The work conducted under the project contributes new knowledge to road design, road traffic engineering and road maintenance. It also enhances methods for advanced numerical simulations of crash tests based on data from experiments. With no or inappropriate road safety equipment, it is important to improve models for estimating road accidents and their consequences. Models are very helpful with planning and designing road infrastructure.

Because road safety equipment and how it is used under different road and traffic conditions has an effect on its functionality and safety, it is important to study these areas and use the results to formulate modern methods for the design, construction and operation of road infrastructure giving sufficient emphasis to the role of the equipment in ensuring the safety of road infrastructure.

The results of the research will be used to develop a set of recommendations for formulating new guidelines for designers, manufacturers and constructors of road safety equipment and for formulating instructions for maintenance firms. Thanks to the guidelines road infrastructure safety will improve and the most common mistakes can be eliminated. For years roadside environments have been one of the most neglected aspects of road safety efforts in Poland. Clarity is needed on the effects of roadsides on road safety. We must understand the hazards roadsides cause and implement effective solutions.

Acknowledgment

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