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ACCURACY ASSESSMENT OF THE TRAFFIC SAFETY MODULE ON TWO-LANE RURAL ROADS

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Abstract. EU countries use a design methodology based on the traffic safety module, proposed by the German scientist R. Lamm. This methodology makes it possible to identify potentially high-risk sections of the road that can become dangerous sections or "black spots" in the future, even at the design stage. This methodology has not yet been implemented in the provisions of the Lithuanian road design normative documents. During the analysis of the traffic safety module results obtained during the previous research carried out by the authors, the impression was created that some of them are wrong. Therefore, in this research, it was decided to also perform a natural experiment by passing the investigated road sections by car. The purpose of this research is to evaluate the accuracy of R. Lamm traffic safety module. The paper presents results of the experiment and their comparison with the predictions of theoretical research.

Keywords: curvature change rate, traffic safety module, turning angle, two-lane road.

Introduction

During research started in Western Europe and the United States of America (Al-Sahili & Dwaikat, 2019; Bauer & Harwood, 2013; Gintalas, 2010), it was found that the main cause of traffic accidents that occur on two-lane rural roads is sudden speed changes between individual elements of the horizontal alignment. It was decided to create an objective and reliable design methodology that would prevent sudden changes in speed and guarantee effective design solutions for the horizontal alignment.

In the practice of other countries, most of the traffic safety assessment models used are based on accident prediction models, which were developed using four main methods, i.e., multivariate analysis, empirical Bayesian method, set logic, and neural networks (Elvik, 2019; Jasiūnienė, 2012).

Hadi et al. (1995) proposed a traffic accident prediction model for two-lane roads in both urban and rural areas. The dependent variables were the total crash rate or the crash rate with injuries. The values of these crash indicators were calculated as a function of the average annual daily traffic (AADT) and the environmental factors. Analysing the influence of traffic flow on the accident rate, it was concluded that the accident rate increases with increasing AADT on roads, and the accident rate decreases depending on AADT on roads with lower traffic. By applying Poisson and negative binomial regression models, the obtained results showed that at low traffic, free-flow conditions exist, so as AADT increases, drivers' freedom of manoeuvre is increasingly restricted, which is associated with a lower probability of a traffic accident.

Persaud et al. (2000) was one of the first to perform a separate analysis of road curve and tangent on two-lane roads. Here, the dependent variable was the frequency of traffic accidents and the independent variables were the traffic flow and the geometry of the road. It was found that the frequency of traffic accidents in curves increases depending on the AADT, the length of the curve, and the curvature change rate. On tangents, the annual number of traffic accidents increases depending on the AADT and its length (Persaud et al., 2010).

Abdel-Aty and Radwan (2000) used the negative binomial distribution to predict crash rates as a function

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of AADT, degree of horizontal curve, length of curve, width of lane, width of shoulder, width of carriageway, and urban/rural road function. The results showed that the frequency of traffic accidents increases depending on the AADT, the degree of the horizontal curve, and the length of curve.

In 2000 in the United States of America, the Federal Highway Administration of the Department of Transportation developed an Interactive Safe Traffic Model, which is used to assess the influence of existing and designed road geometric parameters on traffic safety and is used for two-lane rural roads, but the traffic accident prediction model can also be applied to other roads and main city streets.

Turkish researcher Atashafrazeh and Yadollahi (2013) performed a traffic safety analysis on rural roads, based on the traffic safety module of the German researcher R. Lamm (Lamm et al., 1995, 1996), which the researcher expanded with additional parameters. In his study, he found that the accident rate is directly correlated with the parameters of the horizontal alignment elements: in 8 years, out of 40 sections of the road where traffic accidents occurred, 13 of them were recognised by the traffic safety module used by the researcher.

The Italian scientist Cafis et al. (2007) proposed a method of assessing traffic safety on rural roads based on the safety index (SI). The method is based on the relationship between the elements of the horizontal alignment and the evaluation of traffic safety according to the established criteria. SI is formed by combining 3 risks and is expressed by the coefficients of impact, traffic accident frequency, and traffic accident severity. The AADT is used to determine the impact factor.

It can be noted that such quantities as traffic flow intensity, accident rate, etc. are commonly used for the evaluation of traffic accidents. All the mentioned methods of predicting traffic accidents are intended to identify a dangerous section for traffic safety, but not a specific dangerous element of the horizontal alignment.

When preparing road construction or reconstruction projects, it is important not only to properly design individual elements of horizontal road alignment, but also to properly coordinate them with each other.

The German researcher R. Lamm (Lamm et al., 2007) developed a method for the determination of traffic safety criteria (TSC) and traffic safety module (TSM) based on the road curvature change rate.

1. Review of the traffic safety module

1.1. The concept of curvature change rate

Research carried out in Western European countries and the USA on low-volume roads, which included various geometric parameters of the horizontal alignment, showed that there is a relationship between real driving speed and accidents. This is shown by the curvature change rate of a single curve CCR_S (Lamm et al., 2007). It was also found that all other investigated geometric parameters do not have a decisive influence on the accident rate.

The concept of *CCR* is applied to describe both a separate element of the horizontal alignment (horizontal curve or tangent) and the horizontal alignment of the entire road. The *CCR* of the horizontal curve is the ratio of the angle of turn of the section to the length of the curve. The total *CCR* of the road is the ratio of the sum of the absolute values of the turning angles of the road to the total length of the curves.

In general, CCR_S of the single horizontal curve with transition curve is calculated by formula (1):

$$CCR_{Si} = \frac{\frac{L_{P1}}{2R} + \frac{L_A}{R} + \frac{L_{P2}}{2R}}{L} \times \frac{200}{\pi} \times 10^3, \text{ gon/km}, \quad (1)$$

where: $L = L_{P1} + L_A + L_{P2}$ – total length of the curved section, m; L_A – length of the circular curve, m; R – radius of the circular curve, m; L_{P1}, L_{P2} – lengths of the first and second clothoids.

$$CCR_{Si} = \frac{\frac{L_A}{R} \times 63\,700}{L_A}, \text{ gon/km}; \quad (2)$$

$$CCR_{Si} = \frac{\left(\frac{L_{P1}}{2R} + \frac{L_{P2}}{2R} + \frac{L_A}{R}\right) \times 63\,700}{L}, \text{ gon/km}. \quad (3)$$

The average *CCR* of the horizontal alignment of the existing road is determined by the formula (4):

$$CCR_s = \frac{\sum_{i=1}^{i=n}\left(\left(CCR_{Si} \times L_i\right)\right)}{\sum_{i=1}^{i=n} L_i}, \text{ gon/km}, \quad (4)$$

where: CCR_S – average curvature change rate of a road horizontal alignment; CCR_{Si} – curvature change rate of a single curve *i*; L_i – length of curve *i*.

1.2. Analysis of the tangents

When reconstructing or building new roads, it is necessary to properly design the tangents of the horizontal alignment. From the point of view of traffic safety, the tangents are divided into two groups:

- Independent (long and medium length tangents), which affect the level of accidents on the road, because the speed of cars can be significantly higher on them than on the adjacent horizontal curves;
- Dependent (short tangents).

The tangents are divided into independent and dependent design elements according to the speed *V*85, which can be achieved when the car drives on the tangent and adjacent horizontal curves (see Figure 1).

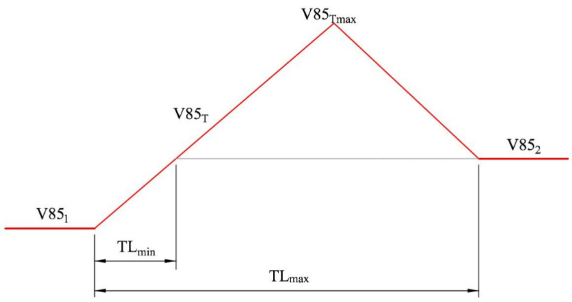

Figure 1. The scheme for determining speeds and lengths in tangents (Lamm et al., 2007)

Where: $V85_1$, $V85_2$ – speeds *V85* in the first and second curves; $V85_{Tmax}$ – maximum operated speed in the tangents; $V85_T$ – operating speed in the tangents (can reach the value $V85_{Tmax}$); *TL* – length of tangent between two curves; TL_{min} – distance required to reach speed $V85_2$; TL_{max} – distance required to reach speed $V85_{Tmax}$.

When $TL \geq TL_{max}$, the tangent is independent (long), it is taken into account, and the length of the tangent is sufficient for the car to reach the maximum speed $V85_{Tmax}$. A tangent and curves are directly related, and the speed of a car in curves depends on the speed in a tangent:

$$TL_{\max} = \frac{V852^2_{T\max} - V85^2_1}{2 \times 3.6^2 \times a} + \frac{V85^2_{T\max} - V85^2_2}{2 \times 3.6^2} = \frac{2 \times V85^2_{T\max} - V85^2_1 - V85^2_2}{22.03}, \quad (5)$$

where a – an average acceleration of the car, 0.85 m/s^2.

When $TL_{min} \leq TL \leq TL_{max}$, the tangent is independent (of average length), it is taken into account, although the length of the tangent is not sufficient for the car to reach the maximum speed $V85_{Tmax}$, the tangents and the curves are directly related – the speed of the car in the curves depends on the speed in the tangent, which at this is calculated by formula (7):

$$V85_T = \sqrt{\frac{V85^2_1 + V85^2_2 + 2 \times 3.6^2 \times a \times TL}{2}} = \sqrt{\frac{V85^2_1 + V85^2_2 + 2 \times 3.6^2 \times 22.03 \times TL}{2}}; \quad (6)$$

$$TL_{\min} = \frac{\left|V85^2_1 - V85^2_2\right|}{2 \times 3.6^2 \times a} = \frac{\left|V85^2_1 - V85^2_2\right|}{22.03}. \quad (7)$$

When $TL \leq TL_{min}$, the tangent is dependent (short) and is not taken into account; the first and second curves are directly related: the speed of the car in the second curve depends on the speed in the first curve.

2. Traffic safety criteria and traffic safety module

The road design methodology, in which the horizontal alignment is considered as a consistent sequence of interconnected elements, is based on quantitative criteria, called traffic safety criteria (TSC):

- The first criterion is the constancy of the design speed V_P;
- The second criterion is the constancy of the speed *V*85;
- The third criterion is dynamic stability in curves.

The constancy of the design speed V_P means that the design speed must be constant over the longest possible road sections. The stability of the design speed is good when the difference between the speed *V*85 and the design speed V_P does not exceed 10 km/h.

Speed *V*85 on a certain road section is related to the curvature change rate CCR_S of this section and is calculated by the general regression equation for the speed *V*85 of the countries of the world. When the longitudinal slope of the road $i \leq 6\%$ and the curvature change rate $CCR_S \leq 1600$ gon/km, the speed *V*85 is calculated using the formula (8):

$$V85 = 105.31 + 2 \times 10^{-5} \times CCR_s^2 - 0.071 \times CCR_s, \quad (8)$$

where CCR_S – general curvature change rate of the horizontal alignment of the existing road.

Constancy of speed *V*85 – speed *V*85 must be constant between two adjacent road horizontal alignment elements (between two adjacent horizontal curves or between a tangent and a curve). Constancy of speed *V*85 is good when the difference in speed *V*85 in two adjacent elements of the road horizontal alignment does not exceed 10 km/h.

Dynamic stability in curves is a criterion for the stability and economy of car driving. The criterion of dynamic stability in curves is based on the comparison of the design (acceptable) assumed side friction coefficient f_{RA} and demanded side friction coefficient f_{RD}.

The side friction coefficient f_{RA} is related to the design speed V_P and is calculated by the formula (9):

$$f_{RA} = \frac{V_P^2}{127 \times R} - e, \quad (9)$$

where: R – the radius of the horizontal curve; e – cross slope of the carriageway in a transition curve.

The required side friction coefficient f_{RD} is related to the 85 percent speed *V*85 (real driving speed):

$$f_{RD} = \frac{V85^2}{127 \times R} - e. \quad (10)$$

The difference between the assumed side friction coefficient f_{RA} and the demand side friction coefficient f_{RD}, which defines a "poor" section, is equal to –0.04.

It is determined that three TSCs:

- The first – separately for each road horizontal alignment element (curve or independent tangent);
- The second – for two consecutive road horizontal alignment elements (independent tangent and curve or two curves);
- the third – separately for each curve.

The algorithms for determining TSCs are presented in Figures 2–4.

For the general analysis of the safety of the road, all three criteria are combined into one system, the traffic safety module (TSM). Project levels are distinguished in the module:

- Good design level – weight factor +1, no correction is required for the element of road horizontal alignment;
- Sufficient design level – weight factor 0, engineering measures to improve traffic safety are recommended for the element of road horizontal alignment;
- Dangerous design level – weight factor –1, the element of road horizontal alignment must be adjusted.

There is a speed relationship between the radii of the horizontal curves and the lengths of the tangents. Lines are dependent and independent. This is demonstrated by

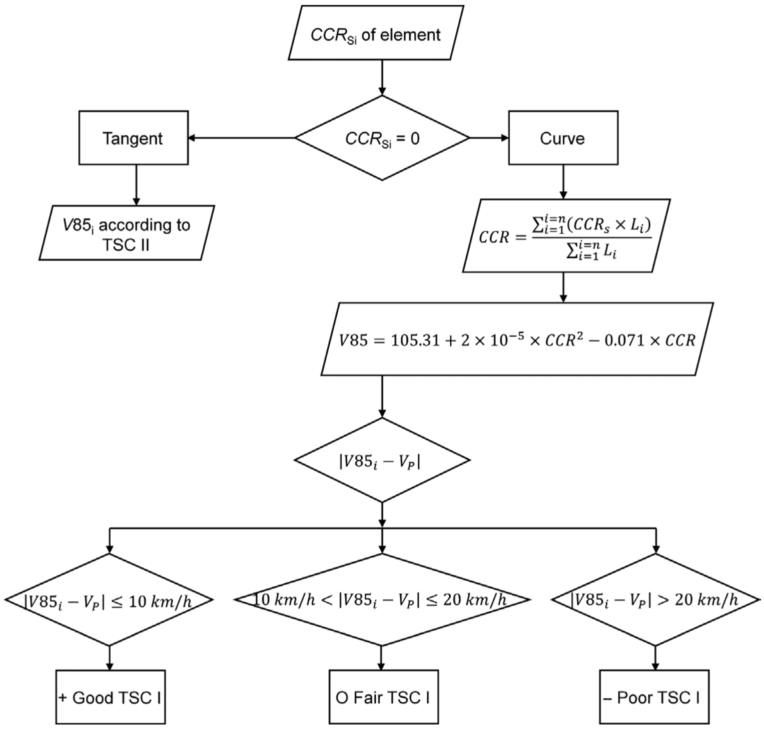

Figure 2. Algorithm for determining of the first TSC design level (made by the authors)

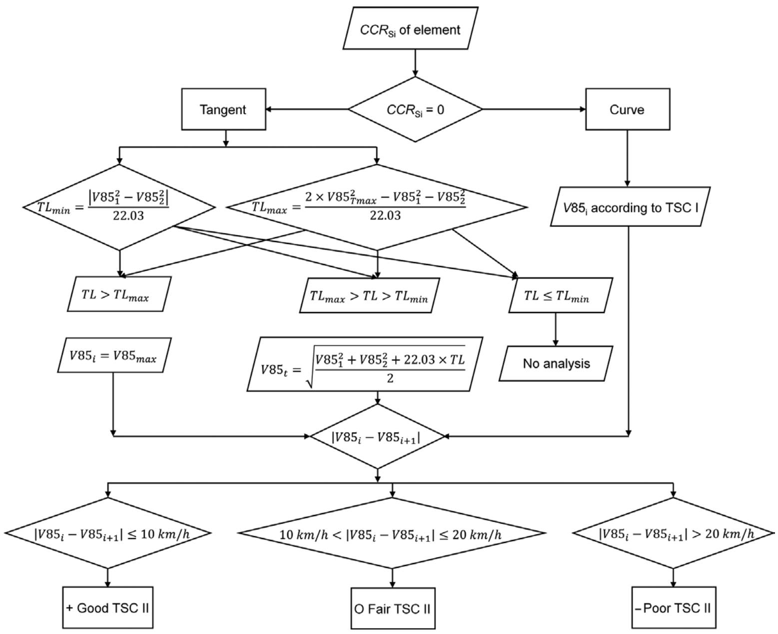

Figure 3. Algorithm for determining of the second TSC design level (made by the authors)

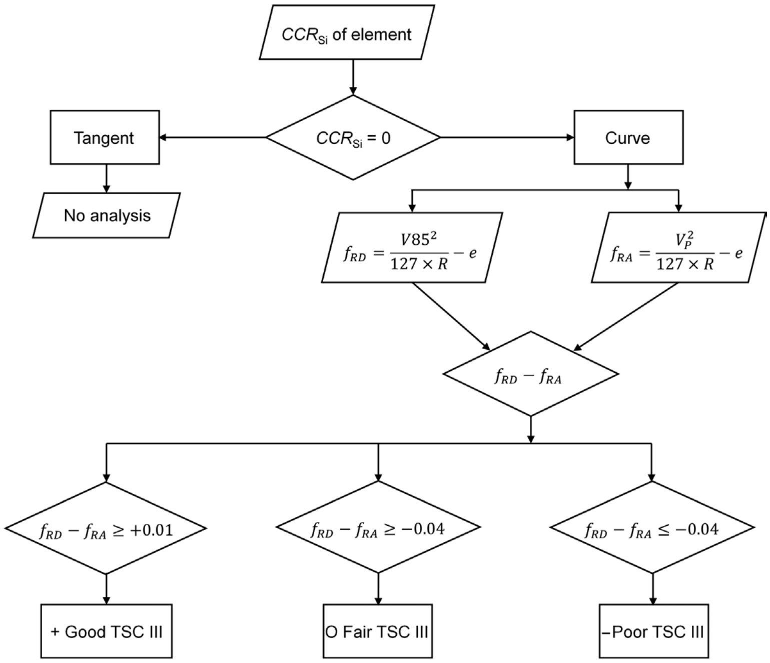

Figure 4. Algorithm for determining the third TSC design level (made by the author)

the 85 percent speed $V85$ simulation problem between elements of horizontal alignment of the road:

- speeds on horizontal curves is calculated by formula (8);
- speed in a tangent:

$$V85_T = \min\begin{pmatrix} \min(V85_1, V85_2) + \Delta V85 \\ 105.31 \end{pmatrix}; \tag{11}$$

– The tangent length is calculated using formula (5).

Combining formulas (5), (8), and (11) gives the final expression for the length of the line (Gintalas, 2010):

$$TL = \min\left(105.31 + 2\times10^{-5} \times \left(\frac{63700}{\min(R_1, R_2)}\right)^2 - 0.071 \times \frac{63700}{\min(R_1, R_2)} + \Delta V85\right) - 1006.8 - \frac{2.9895\times10^8}{R_1^4} + \frac{3.3321\times10^7}{R_1^3} - \frac{1.7044\times10^6}{R_1^2} + \frac{43240}{R_1} - 1006.8 - \frac{2.9895\times10^8}{R_2^4} + \frac{3.3321\times10^7}{R_2^3} - \frac{1.7044\times10^6}{R_2^2} + \frac{43240}{R_2}. \tag{12}$$

TL values corresponding to a short or long line:

- when $TL \leq TL_{\min}$ (short, dependent tangent), the curves are directly related, the speed of the car in one curve depends on the speed in the other;
- when $TL \geq TL_{\max}$ (long, independent tangent), the length of the tangent is sufficient for the car to reach the maximum speed $V85_{T\max}$ = 105.31 km/h.

3. Experiment by passing the research road sections by car

The object of the investigation is the methodology proposed by R. Lamm, which is applied to determine the level of traffic safety on two-lane rural roads. The purpose of the research is to assess the accuracy of R. Lamm's TSCs' and TSM methodology.

Theoretical analysis suggests that the CCRS values are not influenced by road horizontal alignment of the road, but does not yet unequivocally prove that this is the reason why TSM has limited accuracy. A natural experiment was carried out by passing selected sections of the road by car.

3.1. Experimental research methodology

The research object consists of seven regional road sections that were reconstructed during the implementation of the gravel road reconstruction programme (laying asphalt pavement). The total length of the sections selected for the research is 29.125 km (see Table 1).

When compiling the research object, the principle of correct sampling was taken into account, the less the measured quantities differ from each other, the more research cases need to be selected, if one wants to determine the reliability of their difference. Therefore, sections with the greatest possible differences between each other were selected: different lengths of sections, different quantity of horizontal curves, the number of traffic accidents that occurred before and after the reconstruction of the road, etc.

The experiment was carried out passing the research sections by a passenger car under normal meteorological

Table 1. Road sections where the experiment was carried out

No.	Road No.	The beginning of the section under consideration	The end of the section under consideration	The length of the section	Number of curves	Creditable accidents before reconstruction	Creditable accidents after reconstruction
		km	km	km	amount	amount	amount
1	2711	1.990	7.840	5.850	9	5	2
2	2716	0.890	3.000	2.110	3	0	1
3	4604	12.470 17.700	15.650 22.870	3.180 5.170	11 10	2 1	5 8
4	4606	21.100	23.050	1.950	5	1	0
5	4610	0.400	6.120	5.720	19	2	1
6	4613	3.970	7.000	3.030	5	0	0
7	4625	0.000	2.565	2.565	9	0	1
Total:				29.125	71	11	18

conditions, when the surface was dry or wet, when it was not raining or snowing.

A Volkswagen Golf4 passenger car with new tires was chosen for the experiment. The crew consisted of two researches. Researcher 1 – the driver was chosen with sufficient driving experience and was considered as average statistician driver. Researcher 2 sat next to Researcher 1.

Tasks of Researcher 1:

– Try to drive at the speeds indicated by the passenger;
– Inform the passenger about his actions with pre agreed phrases: "danger", "reducing speed", "breaking".

Tasks of Researcher 2:

– to indicate the driving speeds to the driver;
– fill in preprepared forms by recording the actual driving speeds of the car and the driver's reactions and actions in the horizontal curves.

Researcher 2 instructed Researcher 1, the driver, at what speed to enter the nearest curve. The indicated speed was the value of speed $V85$, which, in turn, depended on whether the tangent before the curve was dependent or independent. The calculated and indicated to the Researcher 2 during the experiment were presented in the reports of the natural experiment. The maximum indicated driving speed was 105 km/h.

For the general analysis of the safety of the road, all three criteria are combined into one system, the traffic safety module (TSM). Project levels are distinguished in the module:

– Good design level – weight factor +1, no correction is required for the element of road horizontal alignment;
– Sufficient design level – weight factor 0, engineering measures to improve traffic safety are recommended for the element of road horizontal alignment;
– Dangerous design level – weight factor –1, the element of road horizontal alignment must be adjusted.

Researcher 1 informed the passenger about his reactions and actions in pre-agreed phrases:

– "danger" – speed is not reduced in the curve, but researcher 1 does not feel completely safe;
– "Reduction of speed" – there is a danger on the curve, the speed is reduced by releasing the accelerator pedal;
– "breaking" – there is a great danger in the curve, the speed is reduced by pressing the brake pedal.

The experiment was carried out by driving in the test sections in both directions (forward and backward). If necessary, the runs were repeated until it was possible to record the speeds and the driver's reactions and actions in all the planned elements of the road horizontal alignment.

The results of the experiment were interpreted as follows:

– Researcher 1 felt safe or the phrase "danger" was spoken – the section (curve) was assigned to a good design level;
– "reducing speed" – assigned to the average design level;
– "braking" – assigned to the dangerous design level.

The accuracy of the TSM was evaluated based on how the module determined the sections (curves) of the dangerous design level.

3.2. Experimental results and their comparison with theoretical research predictions

Results of a natural experiment on roads and comparison with the calculated theoretical TSM:

– Two dangerous curves were identified on road No. 2711; TSM identified only one of them as dangerous; the assumption that the TSM result on one of the curve's is incorrect has been confirmed;
– In road No. 2716 dangerous curves were not identified; TSM and experimental results were the same;
– In road No. 4604 (section from 17.470 km to 22.648 km) no dangerous sections have been identified; TSM identified four dangerous curves; the assumption that the TSM result in curve No. 2 is incorrect was confirmed and there was no assumption that this curve was safe;

- On road No. 4606 dangerous curves were not identified; TSM and experimental results were the same;
- Two dangerous curves were identified on road No. 4610; TSM identified four dangerous curves in forward direction and three dangerous curves in backward direction; the assumption that the TSM result on one of the curve's is incorrect was confirmed and there was no assumption that this curve is safe;
- One dangerous curve was identified in road No. 4613; TSM and the experimental results were the same;
- One dangerous curve was identified on road No. 4625; TSM has not identified no one of curves in this road as dangerous; the assumption that the TSM result on this curve is incorrect has been confirmed.

The results of the natural experiment show to us that:

- Errors in the TSM results are significant to the extent that the module reflects reality only partially; the theoretical TSM correctly identified only 33% of potentially dangerous places;
- Significant errors in TSM are influenced by the current method of calculating the curvature change rate CCR_S;
- An alternative approach to curvature change rate is needed.

The results of the experiment could be subjective. The actions of Researcher 1 (driver) were influenced by Researcher 2. During measurements there was limited accuracy, because driving speeds and driver's actions were recorded only at separate moments, speeds were recorded only with an accuracy of 5 km according to the speedometer readings. More accurate results of the experiment would be obtained using sensors that would continuously record driving speeds and driver actions. Furthermore, it is likely that a larger study sample is necessary for the statistical reliability of the results.

Conclusions

1. Based on the review of road safety assessment methodologies, it can be stated that the idea of traffic safety criteria and traffic safety module proposed by researcher R. Lamm is undoubtedly innovative, and the methodology developed on the basis of this idea is logically complete and recognised in many countries. Assuming that traffic safety module produces results with a level of accuracy that corresponds to reality, the application of this methodology in practise offers important advantages:
   - It is possible to justify the design speed in the calculations and thus avoid fundamental errors in the preparation of road reconstruction or construction projects;
   - It is possible to identify potentially dangerous elements (sections) both at the stage of preparing design solutions and on the road already in use, while "black spots" were not identified due to random circumstances.
2. The results of the theoretical and experimental research performed rejected the assumption that traffic safety module has sufficient accuracy – the accuracy of the module is only 33% when determining potentially dangerous sections on two-lane rural roads.
3. Research has shown that significant errors in traffic safety module are determined by the current method of calculating the curvature change rate CCR_S, which can be considered insufficiently justified from a mathematical point of view.
4. The results of the research performed show that the methodology of traffic safety criteria and traffic safety module can be improved by specifying the current curvature change rate CCR_S calculation.

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