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Optical Quality Assessment of a Motorway Route

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Abstract. A roads and highways are a complex structures consisting of different geometric and structural elements. Some of those elements influence the driving comfort, speed and traffic safety whereas others contribute to motorway durability and its proper function during different seasons of a year. The development of motorway construction or reconstruction designs either relies or is about to rely on the principles of spatial design of a motorway route. The application of the said principles improves optical quality of the route and leads to a correct comprehension of the motorway concerned. Nevertheless, the global as well as the European and the Lithuanian experience witnesses the cases of the emergence of unavoidable optical deformations in the solutions of motorway route design and the reason for that could be an unavailability of clear requirements set forth in the relevant standard documents in force in regard to coordination between the horizontal alignment and the vertical alignment of motorway elements. The missing coordination between the solutions of horizontal alignment and vertical alignment of the motorway turns to be the cause for lower levels of driving comfort and traffic safety, as an adequate prevision of the current situation driving such a motorway cannot always be possible. A parameter known as Curvature Change Rate of single curve (CCRs) is applied by numerous countries to assess the quality level of horizontal alignment of the existing or design motorway route. The present article presents a variation of the vertical alignment of a motorways in Lithuania relying on Curvature Change Rate of vertical curve (CCRv) parameter.

Keywords: road safety, road design, geometric design, horizontal alignment, vertical alignment.

Conference topic: Roads and railways.

Introduction

Road geometric design refers to the calculations and analyses made by the designer to fit the road to the topography of the site while meeting the safety, service and performance standards. It is mainly concerned with the elements of the road that are visible to the drivers and users. However, the designer must also take into consideration the social and environmental impacts of the road geometry on the surrounding facilities. Usually, the road geometric design has the following objectives:

- To design a road that provides, in a cost-effective and safe manner, an adequate level of service to meet the needs of all road users, including pedestrians, cyclists and motorcyclists.
- Determine within the allowance permitted by the design standard and road reserve, the routing of the proposed road.
- Incorporate, within the design standard, various physical features of the road alignment to ensure that drivers have sufficient view of the road (and obstacles) ahead for them to adjust their speed of travel to maintain safety and ride quality.
- Provide a basis for the road designer to evaluate and plan for the construction of a section of the proposed road.

Road geometry is usually studied and designed in terms of three components – horizontal alignment (Liu *et al.* 2014), vertical alignment and cross-section – which define a roadway as three-dimensional ribbon. The design of those three components is made sequentially (in a static or in a dynamic way) and they should be coordinated according to the existing design standards. It is mainly the horizontal and vertical alignments that should be well coordinated in order to have a good result in the three-dimensional alignment. Such coordination is better achieved using software tools that show the road project in three dimensions, covering the right-of-way and adjacent terrain – how the road fits into the landscape (Vitkienė, Puodžiukas 2014).

In essence, hasty design solutions that may turn out to be improper in terms of traffic safety occur in lower category roads, especially those attributed to distribution and particularly to access roads. Frequent practice observed in the road sector of this country is an attempt to keep the deviation of the design road axis of the reconstructed road sections from the existing axis as little as possible ascribing this to the aspiration to minimize the reconstruction costs. The engineered speed reduction measures and speed limit road signs are used as an alternative for the adjustment of horizontal and vertical alignment of a road. Besides, the solutions of horizontal and vertical alignment are developed separately, as a general rule.

The current practice is doubtful enough thus an unavoidable necessity for conducting a number of researches has been faced in order to verify the quality of design solutions at the very initial stage of design development. The present article introduces one of the numerous analyses intended to assess the coherence of design solutions with the visual road quality and the right road perception requirements.

Design of motorway route elements, quality assessment of design solutions

While travelling on roads a driver judges about the road trajectory variations relying on straight sections and horizontal and vertical curves. No hairpin curves will be anticipated by a driver if the road is straight and there are no abrupt curves. On the other hand, when the curves of the road are numerous, the driver will keep expecting more bends along his drive forward.

The knowledge of road geometry (Maltinti 2012; Rosey, Auberlet 2012; Bella 2015) is one of the necessary requirements set forth to guarantee higher traffic safety standards. Drivers, in fact, are influenced by road geometry because they adapt their behaviour of driving to their perceptions, driving ability and accumulated experience in segments they have covered yet (Mascio *et al.* 2012).

Geometric elements should assure sight distances which are one of the most important factors of road safety because they influence the driver's behaviour in choosing the right speed and in making braking and overtaking manoeuvres in safety conditions (Maltinti 2012; Rosey, Auberlet 2012; Bella 2015).

In road design rules of some Western European countries, for example, Germany, in order to make the route smooth the requirements are set to not only the radii of horizontal curves (compared to Lithuanian design rules) but also to the minimum lengths for curves.

The German (Forschungsgesellschaft... 2012) shows the various element sequences in which transition curves are used. The defined minimum lengths for horizontal circular curves do not allow designers to use very short curves and this enable to reduce road bendiness dangerous to traffic. Besides, this regulated length enables to determine a design step in horizontal alignment which depends on design speed. In this way, limitations are set to road bendiness which influences LOS and it is ensured that the road alignment is safe, smooth and convenient for the drivers. To ensure safe transitions, the radii of curves after straight sections should have a balanced relation to the length of the straight section. Both directions of traffic should then be considered. Straight sections between curves of the same direction should be avoided. If this is not possible, the minimum length of the straight section should be 1.5 times the radius of the smaller curve (Vitkienė, Puodžiukas 2014). In comparison with the values included in a practical manual Sustainable Safe Road Design (2006) published by the World Bank and the Dutch Ministry of Transport, Public Works and Water Management, the values of horizontal radii contained in the Lithuanian design standards are quite different from those applied abroad.

The notion of spatial design in the current design standards in force in the Republic of Lithuania is not used at all. Moreover, no mention about coordination between spatial road elements is given therein. The valid design standards read that the selection of horizontal curve radii is dependent on the design speed. Crest and sag vertical curves are needed in the locations of the straight line turning points of the road longitudinal profile design line. It is recommended that the selected radii for the curves in question together with the elements of horizontal alignment are in smooth spatial line of the route and ensure necessary stopping visibility, and are tailored to fit the terrain relief and landscape.

Gaca and Kiec (2016) as a result of the research, recommendations for selection of speed for the design with respect to road function have been developed, in lieu of currently used values of design speed. The range of applied speeds for the design at local roads was limited to 60–70 km/h. Cases in which: local speed limits are necessary have also been shown.

(Moreno *et al.* 2016) presented the relationship between operating speed and horizontal alignment, highway bendiness could potentially affect speeds and platooning; and therefore the ideal performance measure should be sensitive to highway geometry variations. The influence of horizontal and vertical alignment on their traffic operation was studied on 19 uniform segments from Spanish two lane highways using TWOPAS (microscopic computer simulation model for two-lane, two-way highways). Alignment was classified following the German procedure: curvature change rate (CCR) and class of gradient. Among the performance measures, follower density was correlated to both traffic and roadway conditions in a more meaningful way.

A spatial image of a combination of road elements has a fundamental influence on the driving behaviour and traffic safety (Forschungsgesellschaft... 2012). A motorway route shall be designed as an optically smooth spatial line combining the elements of horizontal, longitudinal and transversal alignments and tailoring these elements to fit the terrain landscape. Furthermore, impact of the elements on traffic conditions and, primarily, on visual perception of the road shall be assessed, so that the motorway route is timely recognizable, perceivable and is unequivocal to the drivers.

The relevant German design documents (Forschungsgesellschaft... 2012) pay an exceptional attention to spatial design principles of a smooth route. Quite a number of examples of standard spatial elements are given and the standard spatial elements are the following: where the start and end of the route curves almost tally with the start and end of convex and concave curves of the longitudinal alignment and where the displacement of the curve apices of the horizontal and longitudinal alignment in terms of one another fails to exceed 20 percent, where the combinations of spatial elements are given and the prospective image of combinations and positive and negative features of element tuning is derived.

Potentially dangerous road sections most likely to turn into traffic accident sections in the future can be determined during the very start of motorway design stage in case spatial design principles of smooth motorway route are observed. Significant influence on traffic safety is made by the following shortfalls of a road: invisible zones (rise and sink), invisible start of a turn (unclear direction) and an extended turn in a recess. Less influence is witnessed due to a bent turn in the highest point, sudden changes and an optically distorted view.

Non-coordinated horizontal and vertical alignment solutions are decisive for driving comfort and traffic safety since driving on such a road it is not that easy to consider an immediately faced situation right away.

If overlapping elements of horizontal and longitudinal alignment are viewed, the ratio between the horizontal curve radius RH and the sag vertical curve radius RV cannot be selected arbitrarily. The said radii shall be connected or coordinated between. It is demonstrated by the calculations that a satisfactory spatial solution can be achieved with the ratio RH/RV as little as possible. The possible ranges of ratio fluctuation are from 1/5 to 1/10. The basic reason for that is the fact that overlapping of the horizontal curves with the concave vertical curves may mislead a driver and prompt an inadequate image of the current situation, where the surface would seem more advantageous than it is in reality. Provided the ratio values are exceeded, more exhaustive analysis of the road section like that is recommended. The flatter the surface, the larger radii of the convex and concave curves shall be selected with due account given to the radius of the horizontal curve.

The most advantageous variant of the surface is guaranteed relying on good visual perception of the road and water draining, and the driving dynamics factors: it shall be considered with due care that the variation points of the horizontal alignment and longitudinal profile tally as much as possible. This can be achieved if the curves in the horizontal and longitudinal alignment are found in similar coordinates and the lengths are more or less the same. This way the distortion points appear almost in the same place and a sufficient draining slope is guaranteed at zero super elevation points and in horizontal alignment and a sufficient side slope is ensured at zero points in the alignment. With the said coordination one may usually achieve a uniform number of variation points in horizontal and vertical alignment. Besides, the design of super elevation with a moderate rise leads to a sufficient longitudinal slope for draining and it is also possible to equip the locations of low values of longitudinal alignment with super elevation.

In the rolling and uneven surface surroundings with steeper marks it would be more expedient if a road section with stable marks between the ends of the convex and concave curves running in succession is selected. In this case the deformation point on a horizontal surface should be as close as possible to the start of the concave curve. This case of the design enables a driver to recognize the curve starting point on a horizontal surface from afar.

In the event the natural surroundings prevent the designer from making the curve starting points tally, then any change of direction shall be arranged with due consideration given to sufficient visibility ahead along the entire route. In terrains with convex vertical curves, the horizontal curves must never hide.

Influence of design road elements on traffic safety and accident rate

Influence of horizontal alignment on accident rate has been thoroughly investigated by Norwegian scientists. It is maintained by Rune Elvik and Truls Vaa (Elvik *et al.* 2009) that straight motorways with abrupt turns (horizontal curve radii less than 400 m) are qualified as having a high accident rate. Assessment of accident rate in road turns classified as accidental/unexpected made using URF software developed in Norway (URF is an acronym standing for Utforkjørings Risiko Faktor – elimination of road risk factors) points to the fact that the accident rate along the road with accidental turns is the highest. The scarce the accidental turns are, the higher risk of traffic accidents in the said turns is observed. A research undertaken in New Zealand by Matthews and Barnes also discloses similar results – the longer the straight section before a hairpin bend, the higher accident rate in a turn.

Elements of horizontal and vertical alignment may limit the driver's speed, visibility and overtaking possibility (Lamm *et al.* 2007). Though horizontal and vertical alignment elements may be designed separately, the results of global researches indicate that the sequence of elements must be selected in a proper way. Attempts are made to achieve that the design solutions are able to increase traffic safety by simulating a driver to choose a more uniform speed along the entire road section.

Improper design combinations of horizontal and vertical alignment elements may even reduce the expected results and highlight their shortfalls. For the purpose vertical and horizontal elements should be coordinated between.

Two key factors to be taken into account in the road design include the design speed and visibility. Those characteristics on a highway are very dependent on the elements of horizontal and longitudinal alignment. An advantageous combination of these elements enables a higher design speed and a larger visibility distance, and also ensures driver's safety on the road.

As it has been already mentioned in the previous sections, the principles of spatial design assert that along with correct selection of parameters for individual route elements (Gintalas 2010) the following must be coordinated in due manner:

- Elements of horizontal alignment;
- Elements of longitudinal alignment;
- Elements of horizontal and longitudinal alignment between to avoid visual deformations and thus ensure visual smoothness of a motorway route.

The researches carried out in West European countries and the USA encompassed different geometric parameters of a motorway route and concluded that the best coherence of horizontal alignment elements is indicated by CCRS (Curvature Change Rate of single curve). The CCRS notion is applicable for characterization of both, an individual element of the horizontal alignment (horizontal curve) and the entire motorway route.

Curvature change rate of a horizontal curve stands for a ratio between an angle of the route turn and the curve length. Curvature change rate of a motorway route makes the ratio between the sums of absolute values of the route turn angles and the length of the road section. In general, curvature change rate of a horizontal curve is calculated using the below Equation 1:

$$CCR_S = \frac{\frac{L_{P1}}{2R} + \frac{L_A}{R} + \frac{L_{P2}}{2R}}{L} \cdot \frac{180}{\pi} \cdot 10^3 = \frac{|\gamma| \cdot 57330}{L}, \quad (1)$$

where: $CCRs$ – curvature change rate of a horizontal curve, deg./km; $L = L_{P1} + L_A + L_{P2}$ – the total curve length, m; L_A – the circular curve length, m; R – the circular curve radius, m; L_{P1}, L_{P2} – lengths of the first and second transitional curves, m; γ – an angle of the route turn, deg.

A notion of traffic safety module is used for the quality assessment of horizontal alignment solutions in terms of traffic safety assurance. Design levels are distinguished in the module:

- A good design level – no correction is required for the motorway route section;
- A fairly sufficient design level – engineered traffic safety improvement measures are recommended for the motorway route section;
- A dangerous design level – adjustment of the motorway route section is a must.

Analogous principles can also be employed for vertical alignment solutions, i.e. the ones having worked in the practice of horizontal alignment solutions must be also suitable for the solutions of vertical alignment. Moreover, similarly to horizontal curves, vertical curves can also be assessed both, in terms of a radius and an additional parameter, the latter defining the influence of this particular curve on the motorway route.

A notion of an optical quality criterion can be suggested for quality assessment of the motorway route from the perspective of safe spatial design and the below design levels are possible therein:

- A good design level – no noticeable visual deformations are available;
- A fairly sufficient design level – visual deformations are noticeable, though they have no considerable influence on a right perception of the route;
- A poor design level – adjustment of the motorway route section is a must seeking to eliminate or minimize unacceptable visible deformations.

Research methodology

The comprehensive researches of the optical quality of the motor ways consist:

- Initial analysis of curves in the roads projects and/or motorways;
- The establishment of the CCRv dependence on the various variables;
- Establishment of the design level for each category of the motorways;
- Digital modelling of CCRv using roads design software.

In the researches methodology must be described the types of researches including analysis of design documentation, analysis of the existing roads and digital modelling of the curves of the roads with good, fairly and dangerous design level.

In this article were collected main parameters of vertical curves, from the exiting motorways. Based on them, the CCRv, was calculated by the Equation 2.

The background data applied for research purposes consist of the randomly screened solutions of motorway reconstruction designs developed at different times:

- Transit motorway sections – 15.3 km;
- Distribution motorway sections – 9.8 km;

- Access motorway sections – 14.7 km.

All in all, 10 sections have been covered by the research and the total length of these made 43.7 km. and 186 samples were used for analysis.

The below are the stages of visual quality assessment of motorway reconstruction designs:

- Making lists of motorway horizontal and vertical alignment elements;
- Analysis of elements coherence;
- Visualization of design solutions employing the computer-aided design (CAD) system tools.

Initial data processing stands for the preparation for the analyses by making parallel lists of the motorway horizontal and vertical alignment elements, where the following data are given (Table 1):

- the element number;
- the element type (straight line or curve);
- the element start;
- the element end;
- the element length;
- radius (for horizontal and vertical curves);
- attempts have been made to describe the vertical curves by an additional parameter called the Curvature Change

Table 1. Fragment of a list of horizontal and vertical alignment elements

Horizontal aligment elements (H)						Longitudinal aligment elements (V)						
No	Type	Radius	Start	End	Length, m	No	Type	Start	End	Length, m	Radius	*CCR_V*
H1	Straigth		32+95.00	33+25.00	30.00	V1	Curve	32+95.00	33+25.56	30.56	–8000	3.82
H2	Straigth		33+25.00	34+63.82	138.82	V2	Curve	33+25.56	35+36.77	211.21	28000	7.54
H3	Curve	600	34+63.82	36+76.71	212.88	V3	Curve	35+36.77	36+09.63	72.86	–10000	7.29
H4	Straigth		36+76.71	40+91.34	414.63	V4	Curve	36+09.63	37+70.91	161.28	–17000	9.49
H5	Curve	310	40+91.34	44+35.99	344.65	V5	Curve	37+70.91	40+01.55	230.64		

Rate of vertical circle curve (CCRV), which is calculated with a preliminary Equation 2:

$$CCR_V = \frac{L}{|R|} \times 1000, \qquad (2)$$

where: L – the vertical curve lengths, m; R – the vertical curve radius, m.

The equation for parabolic curve is under investigation.

All results of the CCRv investigation, are presented in the Figure 1.

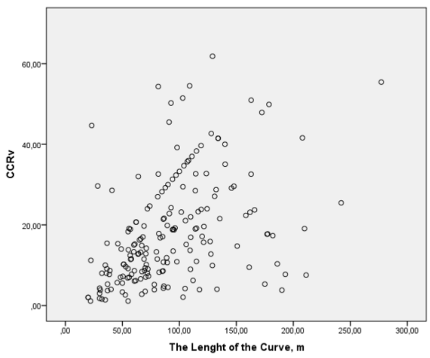

Fig. 1. Distribution of the CCRv values

Descriptive statistics of this research presented in the Table 2.

Table 2. Descriptive statistic of the CCRv

	Min	Max	Mean
CCRv	1.10	61.84	18.17
Length of the Curve	20.00	277.17	91.97
Radius of the Curve	1000.00	50 000.00	8326.12

Horizontal and vertical curves are attributed to properly non-coordinated between in the below cases:

- Length ratio of sag vertical and horizontal curve is more than 1:1.5;
- Mid-shift of sag vertical curve in terms of the centre of horizontal curve makes more than 33%.

For the purpose of determination of a way on how properly non-coordinated horizontal and vertical curves influence the optical quality of a motorway and right perception of a motorway, visualization of design solutions using computer-aided design (CAD) system tools have been performed. Visualization parameters are as follows:

- The position of a compartment simulating a car driver is at 1.2 m height over the carriageway surface and 1 m to the right from the design motorway axis;
- Cross-sections of a motorway are generated at 20 m intervals;
- Visualization is performed both driving directions (downstream the mileage and upstream the mileage).

The shortcoming of the research methodology lies in the fact that visualization results have been assessed in a subjective manner by just a few assessors and no independent experts have been interviewed to reduce the factor of subjectivity to its minimum. Furthermore, the proposed formula of the Curvature Change Rate of vertical curve is merely preliminary.

Results of an optical quality assesment of a motorway route

The results derived in the course of investigation of horizontal and vertical alignment solutions for motorway reconstruction designs in terms of optical quality of a motorway route point to the fact that the presence of properly non-coordinated horizontal and vertical curves in the solutions of motorway reconstruction designs amount to:

- Up to 92% in terms of length;
- Up to 65% in terms of the curve mid-shift.

Generalisation of investigation results conclude into a statement that the functional purpose of a motorway in the research sections has no noticeable influence on the quality of design solutions as regards optical quality of a motorway route. Thus, a probability of a failure to guarantee a proper optical quality of a motorway route in the reconstructed motorway sections does exist.

The below figure (Fig. 2) illustrates examples of visualization of properly non-coordinated horizontal and vertical curves, i.e. the way the motorway section would be seen by a car driver. As one may see in the illustrations above and judge from what has been proven by the research, clearly visible optical deformations are far from being always conditioned by properly non-coordinated horizontal and vertical alignment. It can be stated that with the value of Curvature Change Rate of vertical curve being lower than a certain limit value, coherence of horizontal and vertical curves has no significant influence on an optical quality of a motorway route.

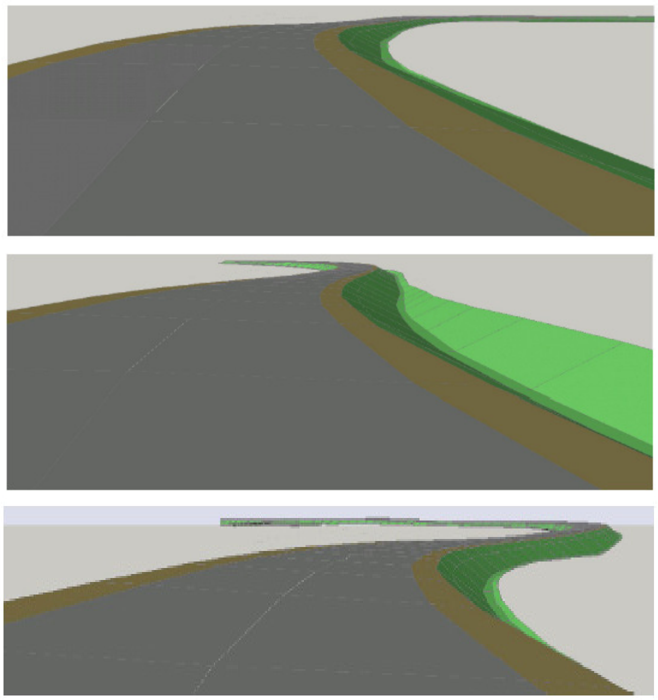

Fig. 2. Visualization of design solutions by computer-aided design (CAD) system tools

More extensive investigations would be needed to answer the question about exact values of Curvature Change Rate of vertical curve that would make the coherence between the horizontal and longitudinal alignment elements preferable or obligatory.

Conclusions

The research initiated for quality assessment of design solutions in terms of spatial design in 10 motorway sections of varying functional purpose has pointed to a failure to apply the spatial design principles in the state significance motorway reconstruction designs in this country.

It has been indicated by visualization of design solutions of a motorway route that non-coordinated solutions of horizontal and vertical alignment of a motorway influence optical quality of the motorway route only in the cases when the vertical curves lead to noticeable optical deformations. Vertical curves, in turn, lead to noticeable deformations in the cases when the ratio of their length and radius is large enough. This ratio can be called Curvature Change Rate of vertical curve CCRV and calculated for either individual curves or the entire motorway section.

The values of the CCRv variate in wide limits, that's indicate, that some motorways were designed without combine of the roads elements.

The equation for calculation for CCRv is preliminary and will be improve based on these researches. The new parameters of the motorways, should be included in this equation.

In order optical deformations are avoided, quality of the vertical alignment can be assessed in terms of Curvature Change Rate of vertical curve CCRV, and an overall quality of the route solutions can be assessed as a consistency between CCRS and CCRV parameters.

The following is recommended:

- The notion Curvature Change Rate of vertical curve should be applied for vertical curves and motorway sections;
- Quality levels (good, fair and poor) of design solutions should be applicable for both, for horizontal and vertical alignment.

With the value of Curvature Change Rate of vertical curve lower than 18, coherence between horizontal and vertical curves has no significant influence on the optical quality of a motorway route and in such cases good level of design solutions is guaranteed, and coordination between horizontal and vertical alignment elements is not necessary. More extensive investigations are needed to find out the exact values of Curvature Change Rate of vertical curve that would make the coherence between the horizontal and longitudinal alignment elements preferable or obligatory.

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