Quantitative methods for the evaluation of spatial alignment of roads

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SYNOPSIS

The international literature concerning spatial road alignment is largely limited to qualitative statements; methods for a quantified evaluation merely treat partial aspects. Up to now there was no user-friendly tool available for the representation of spatial road alignment with an objective assessment as its aim.
Intensive research activity led to the derivation of evaluation criteria from the phenomenon of poor spatial road alignment: sight distance, partial road disappearance from driver's view, sight distortion, sight quality and the sight on changes in curvature.
The evaluation values calculated from perspective image data by means of software can be represented by a length-referenced diagram. The characteristics band for sight quality contains the distance and depth data as well as data concerning the quality of sight (QuaSi-Band).
This newly developed method will assist the design engineer in evaluating spatial road alignment within his day-to-day work practice.

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INITIAL SITUATION

The effective German guidelines and the international literature are largely limited to qualitative statements concerning spatial road alignment. Satisfactory procedures for the representation and control of spatial road alignment criteria are not available – with the exception of perspective images, which can only be analysed subjectively. As a result, spatial road alignment does not get the attention it deserves in day-to-day design practice, even though unfavorable spatial road alignment is a well-known safety-relevant factor. Therefore, the research activities at the Institute for Highway and Railroad Engineering (Institut für Straßen- und Eisenbahnwesen – ISE) of the University of Karlsruhe aimed to work out a practical method for representation and control as well as quantified criteria for the evaluation of spatial road alignment. The results have been extensively documented in the papers published by the ISE (Zimmermann 2001) and will be summarized in the context of this paper.

In addition to the requirements for the geometrical arrangement of the alignment and the roadway course, the effective German guidelines for road layout, RAS-L (FGSV 1995), also provide indications and principles for spatial road alignment, which have largely been taken over from the previous guidelines RAL-L (FGSV 1970). First of all, they contain very general qualitative statements regarding the effects of individual elements or element series and their respective scale in terms of horizontal and vertical alignment. Regarding the overlapping of the horizontal and vertical alignment, sufficiently established principles concerning the optimum position of the turning points in relation to one another were determined ("turning points over turning points") and empirical values concerning the relationship between vertical and horizontal alignment elements indicated. Furthermore, examples are given of what can happen when it is not possible for the vertical and horizontal alignment turning points to coincide.

The illustrations are only partially meaningful to the design engineer, since it is difficult to assign them to concrete design parameters. Nevertheless, the illustrations and corresponding notes concerning the overlapping of the vertical and horizontal alignment provide the only and – at least as far as verbal descriptions are concerned – complete summary of the phenomena to avoid when it comes to spatial road alignment.

The overlapping of crests and curves which due to their position in relation to one another hide relevant areas of the curve ahead hold a special status among the described phenomena of poor spatial road alignment. This is the only phenomenon among those presented which originates from the overlapping of only one horizontal and vertical alignment element each. In principle, the additional phenomena are based on identical overlapping mechanisms; however, their effects and the dangers resulting therefrom are mainly dependent on the markedness of the vertical alignment elements. In principle, these sections can be distinguished from those with good spatial road alignment by the circumstance that within the clearly visible stretch ahead several vertical alignment elements are overlapped by a single horizontal alignment element. Qualitative distinguishing features for warps, fluttering and diving or jumping are especially the number of crests along a stretch within the driver's range of vision and the question of whether partial road disappearance from the driver's view sets in when driving along this stretch of the road.

Furthermore, the RAS-L (FGSV 1995) contains statements about the sag effect, the negative effects of which can be avoided with the help of a good harmonization of the scale of the radii of horizontal and vertical curves. It is a well-known fact that in sag vertical curves in which there is an unfavorable relationship between the vertical and horizontal radii, the driver sees a perspective image of the road band which entices him to drive at a higher or at an excessively high speed and results in a discernible increase in accidents. Mathematical explanations for the effects of such distortions on the driver often refer to "visible radii", but it has been proven that the principles on which this term is based need to be re-evaluated (cf. Osterloh (1983)).

A SIMPLIFIED SIGHT DISTANCE MODEL AND THE DETERMINATION OF PARTIAL ROAD DISAPPEARANCE FROM DRIVER'S VIEW

In the context of the research carried out at the ISE, spatial road alignment was evaluated according to the following decisive criteria: sight distance, partial road disappearance from driver's view, sight distortion, sight quality and sight on changes in curvature. Whereas sight distance and partial road disappearance from driver's view are evaluated via the depth of invisible roadway parts under the respective horizon of the perspective image, the visible roadway surfaces of the examined alignment in comparison with the same horizontal alignment without the influence of vertical alignment and cross fall shall be used to evaluate sight distortion and sight quality. The above-mentioned evaluation criteria and the proposed assessment methodology are briefly explained below.

In general, sight distance as an important alignment element is defined as the geometrical sight distance up to a standing or moveable obstacle in the current (stopping) or desired (overtaking) driveway. The sufficient visibility of an obstacle defined in terms of its position and its height relative to the roadway only suffices as an assessment criterion when an actual spatial evaluation is concerned. However, it does not suffice – as is often still the case – when examining horizontal and vertical alignment separately. Furthermore, an adequate sight of additional decision-relevant elements in spatial road alignment for the driver must also be guaranteed, e.g. the beginning of curves should not be hidden. This makes a shortcoming in the ordinary sight distance bands evident, since each band is assigned a fixed combination of viewpoints and target points in horizontal, vertical and cross-section positioning.

While the specifications of the viewpoint - at least as far as the automobile driver is concerned – can be assumed to remain constant for the most part, the values representing the target point of the sight beam can be modified and adapted to the respective problem.

At present, there are two specifications for the position of the target point in cross-section. Depending on the potential critical obstacle, it is either in the middle of the driver's own lane (stopping sight distance) or in the middle of the oncoming traffic lane (overtaking sight distance). For these clearly defined tasks, the specifications are logically consistent. For a more comprehensive sight distance analysis, which is necessary for many reasons, a wealth of sight distance bands with just as many specifications concerning target points and therefore a substantial level of confusion would result. Thus, the procedure to establish sight distance was fundamentally changed. Instead of discerning the longest possible uninterrupted sight beam for a target point that is specified in terms of horizontal and vertical position, the depth of a specified target point in terms of the horizon is merely defined horizontally in transverse profile to the cross section. If the resulting depth is inferior to the target point height relevant to the respective research problem, then sufficient sight is available.

In order to cover as many research aspects of sight distance as possible with the determination of a cross section point as the target point of the sight beam, the method depicted in Figure 1 was chosen. Up to a distance of 400 m from the observer (scope of the required stopping sight distance), the target point is assumed to lie in the middle of one's own lane, at greater distances (scope of the overtaking sight distance), it is assumed to lie in the middle of the oncoming traffic lane. For additional alignment assessments, the cross section position of the target point is much less important than it is for the stopping and overtaking sight distance. This procedure is also the required basis for assessing partial road stretches in disappearance from the driver's view (e.g. diving and the hidden beginning of a curve according to Figure 2). The relevant features of depth, position and length of partial road disappearance from driver's view can thus be determined for every viewpoint along a given alignment. For the analysis of depth road disappearance – same concerning a partial or the complete disappearance – there is no difference between the case the road is hidden behind a screw or behind a slope. In all cases the depth of the hidden part of the roadway is relevant for the estimation.

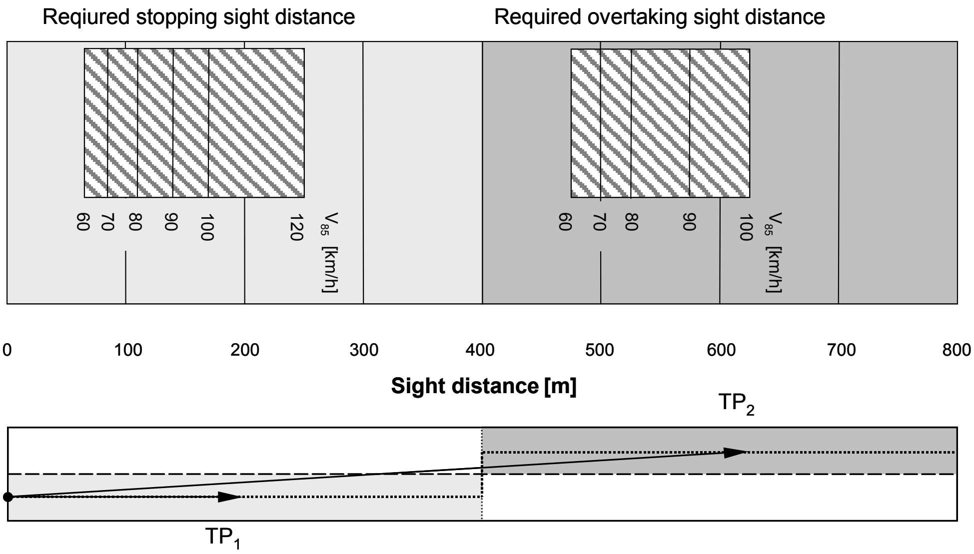

Figure 1: **Required sight distance and position of the target points (TP)**

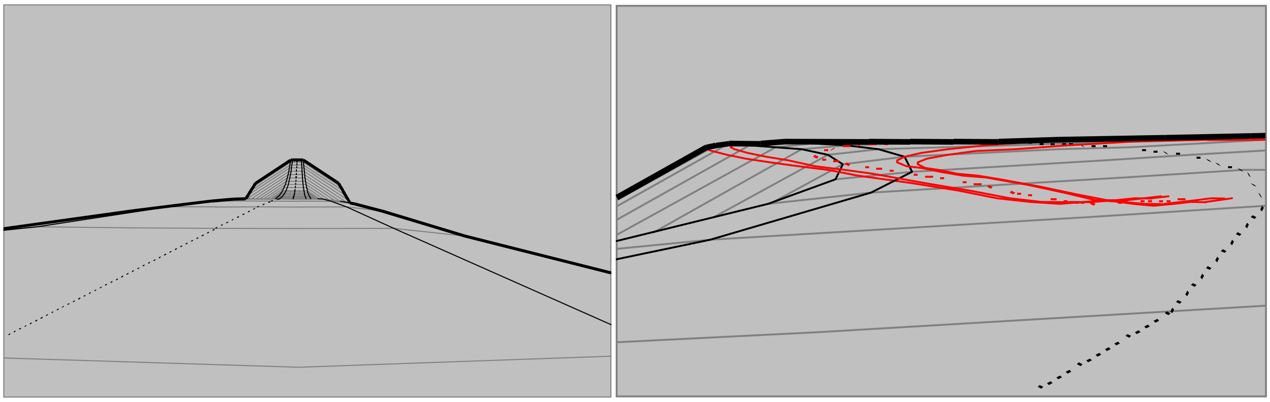

Figure 2: An example of diving and the hidden beginning of a curve

RELATIVELY VISIBLE ROADWAY SURFACES AS A MEASURE OF SIGHT DISTORTION AND SIGHT QUALITY

In order to characterize the visible roadway surfaces for each genuine point of alignment, several values can be used: Since the sag effect which leads to an increase in the visible roadway surfaces is mainly a result of a poor selection of vertical alignment elements, it is evident that in order to reduce the computation efforts merely the incident angle of the sight beam onto the roadway surface should be chosen. If the other conditions, such as cross fall and curve radius are kept constant, this angle is in a direct relationship with the visible roadway surface. However, since cross fall plays an important role when it comes to the driver judging the roadway ahead, the primary feature “visible roadway in a perspective image” should be used as an assessment criterion for sight distortion, since it contains all the influences of the three-dimensional construction that represents a road.

The proportional value of the perspective image surfaces from sag-overlaying and flat horizontal alignment curves is a characteristic feature in terms of distance from the observer and is directly related to the underlying horizontal and vertical alignment as well as the cross-section parameters. In order to evaluate potential illustrative errors due to unfavorable sag vertical curve-horizontal alignment radii combinations, the characteristic course of this proportional value must be standardized so that in the context of a constant cross fall merely the influence of the ratio of H_W to R remains the same. Since it has been proven that for the identical ratios of H_W to R in the vertex of the perspective image exactly identical distortion proportions exist, this value can also be used to assess the illustrative distortion of a sag vertical curve in the end. Figure 3a shows an example for a sag-overlaid curve. In all graphs the surface area between 40 and 60m distance from drivers position is coloured. Visible is the increasing coloured area for decreasing vertical radii, each in comparison to a picture of the same horizontal alignment without influences of vertical alignment and crossfall. The relation between the size of a roadway part of the sag-overlaid curve and the same horizontal curve without these influences characterizes the sight distortion.

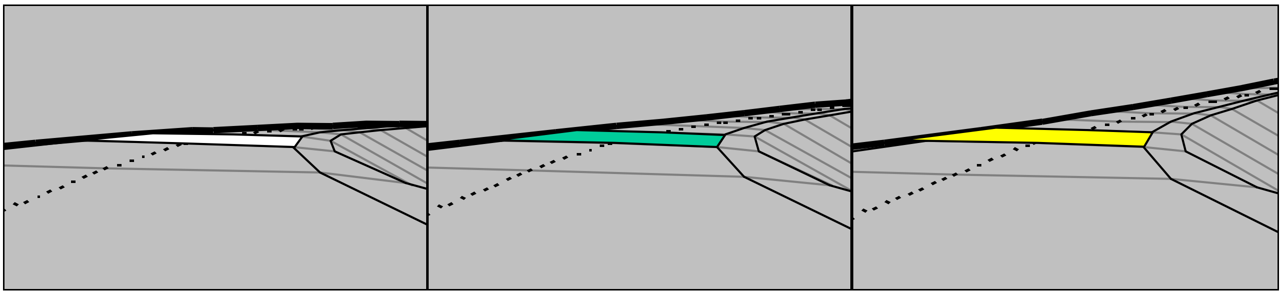

Figure 3a: Example: Visible roadway in a perspective image: Sag-overlaid curve (R=400m; H=∞ m, H=2.000m, H=4.000m)

In this context, it must be mentioned that vertical curvature results in a lesser degree of visible roadway surfaces, i.e. they behave in an opposite manner to sags. Although the assessment of crests in relation to the relatively visible roadway surfaces as well as publications which deal with visible radii and perspective distortions resulting therefrom result in values less than 1, conclusions can not be drawn about the underlying ratios of H_K to R in this context, since the crest effect is only interpreted as an expression of insufficient sight quality.

The starting point for determining a criterion of insufficient sight quality is the same as the one used to assess sight distortion. Just as large stretches of a highly visible roadway surface contribute to an improved optical impression of the road – and thus tend to entice drivers to drive at higher speeds – a less visible roadway surface reduces the road’s optical quality. The effects of this loss in quality are numerous and extend from purely optical shortcomings, such as irregularities in the visible roadway surface in terms of more distant warps of the roadway (Figure 3b) via poor illumination characteristics of sections following warps in the outer range of headlight illumination up to curvature loss in immediately ensuing curves.

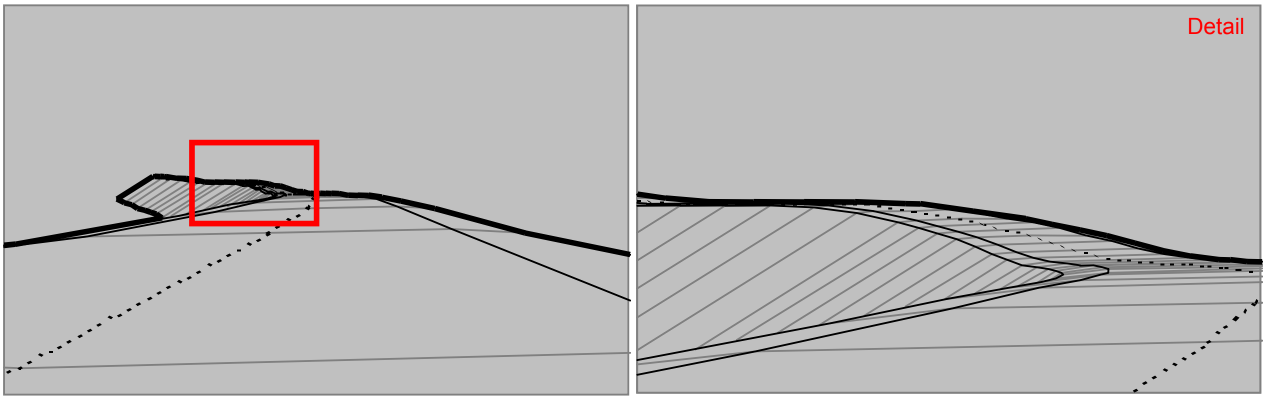

Figure 3b: Example: Warp of a roadway

These examples have in common that neither objectively discernible shortcomings in terms of sight distance nor partial road disappearance from the driver's view show up. Nevertheless, the subjectively discernible shortcomings which combine these and similar examples for poor sight quality lie exclusively in the visibility of the roadway surface. However, the inevitable decrease of the examined surface with increasing distance must be taken into account in a suitable manner as well. Therefore, it seems reasonable - analogously to examining sight distortion – to compute a relation between the actually visible roadway surface for the selected target station of an existing alignment and a comparative alignment with a flat vertical alignment and without cross fall ("relatively visible roadway surface").

REPRESENTATION OF QUANTITATIVE ASPECTS OF SPATIAL ROAD ALIGNMENT IN THE QUASI-BAND

Nowadays, technical perspective images can be produced of any given point of a planned road with the help of data processing via the available horizontal, vertical and cross-section data and with the intersection of a digital terrain model. These images can then be quantitatively evaluated in terms of the above-mentioned assessment criteria for spatial road alignment. Figure 4 shows a graphical representation of an example alignment of this kind of analysis at the selected station 0+300. The conditions of visibility are represented starting from the center of one's field of vision up to a distance of 800 m. In places where the roadway surface is visible, shades of yellow to brown indicate areas with a sight distortion greater than 1 and shades of blue indicate areas with poor sight quality. For sections in which the roadway surface is not visible, the selected colors indicate the depth of partial road disappearance: up to 0.5 m in light-green, between 0.5 and 1.0 m in dark-green and over 1.0 m in red. Furthermore, the exact values for the proportion of the visible roadway surfaces are indicated as a blue line and the depth of partial road disappearance as a black line.

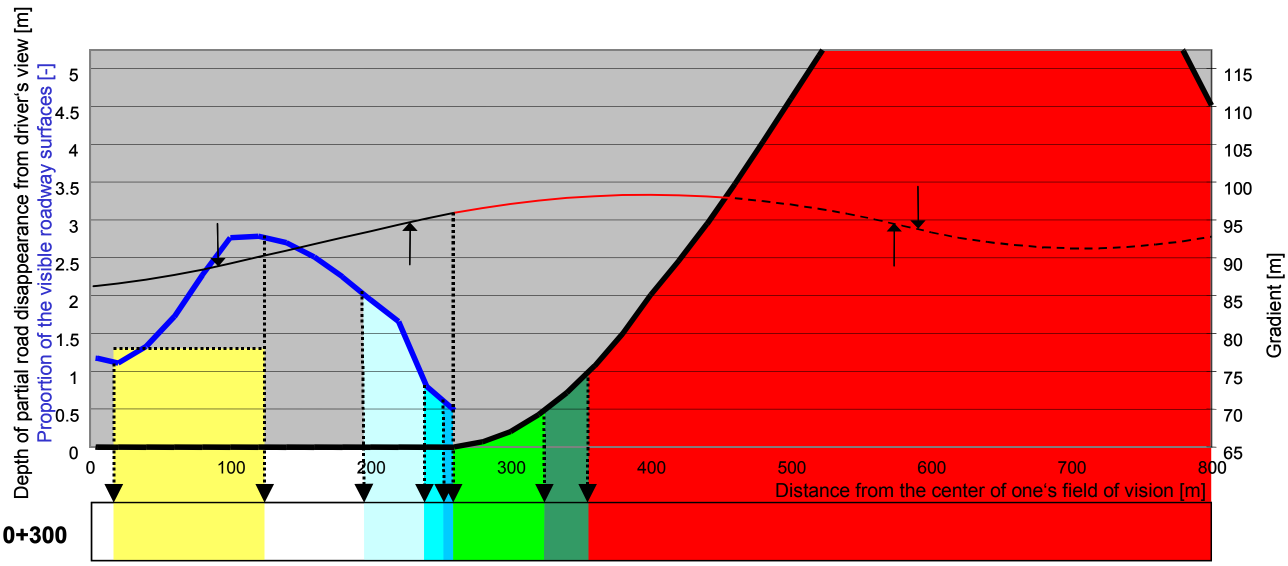

Figure 4: Visibility conditions at station 0+300 of an example alignment

Subsequently, the individual observation of the example alignment at station 0+300 can be transferred to an overall image by marking all the individual observations along a given stretch (e.g. every 20 m) in a characteristics band. This kind of a band which represents data for each viewpoint along a given alignment - equivalent to the currently used sight distance band - regarding sight quality and quantity (QuaSi-Band), is depicted in Figure 5 for a complete example alignment. The middle of the graph shows the corresponding vertical alignment and the curvature band, the sight information is indicated in the stationing direction on the top and in the opposite direction on the bottom. Analogously to Figure 4, every color bar thus corresponds to the analysis of a perspective image at a sight station up to a distance of 800 m. The line of vision runs from the inside to the outside respectively.

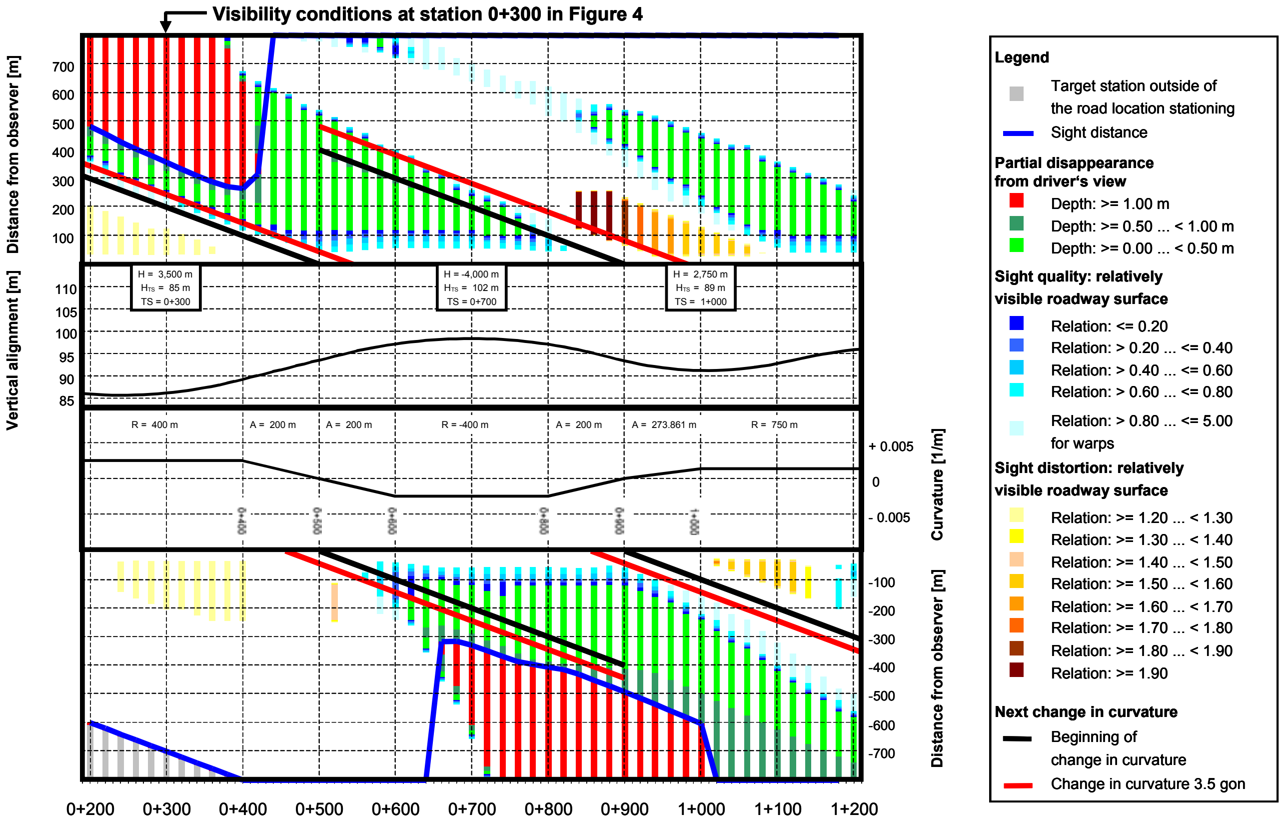

Figure 5: Representation of sight quantity and quality in the QuaSi-Band

Since the same specifications concerning the viewpoint and especially the target points were chosen for the assessment of spatial road alignment as was the case for the model of stopping and overtaking sight distances as per RAS-L (FGSV 1995), modified by a circular of the German Federal Ministry of Transportation concerning new regulations of stopping sight distance, the sight distances determined – i.e. the distance between the viewpoint and the first intersection of the 1 m depth line – can directly be used as a stopping or overtaking sight distance. Therefore, the transition from green to red within the bars corresponds to the defined stopping or overtaking sight distances and is connected by a blue line for the purpose of clarification.

A critical alignment is present when a bar in the line of vision shows a blue marking following a green or red marking. This means that the roadway surface in a specific section is not visible but reappears after a certain distance (e.g. at station 0+700 opposite the stationing direction: deep diving, at station 1+100 in the stationing direction: shallow diving.) The difference in the danger potential lies in the circumstance that the driver can assess a merely shallow partial disappearance from his view in depths ranging up to 0.5 m (light-green) due to the still visible marker post, whereas greater partial disappearance depths (dark-green or red) provide no information on oncoming traffic or the course of the road. This example makes it evident that - contrary to the specifications in the German guidelines for road design, part alignment (RAS-L (FGSV 1995)) - the wavelength until the reappearance of a road should not be taken as a measure of deep and shallow diving (or jumping). Instead, the actual depth of the partial disappearance from driver's view, which was not included in the examination of spatial road alignment in the past and therefore was not assessed, should be used.

This example alignment also enables one to detect additional phenomena of spatial road alignment. For instance, at station 0+700 in stationing direction there is a warp (indicated by a light-blue coloration for poor sight quality) and at station 0+900, the color brown indicates a sight distortion (sag effect). To evaluate the visibility of changes in curvature, the distance to the following change in curvature (black line) as well as the

distance to the decisive change in the angle of deviation of 3.5 gon (red line) are represented in the QuaSi-Band.
Naturally, a certain amount of practice is required to interpret the QuaSi-Band – however, this skill is quickly mastered. It goes without saying that this form of representation for spatial road alignment is of significant importance in practice, since all the relevant aspects of spatial road alignment can be represented quantitatively and in a clear manner for an entire road section. Furthermore, the QuaSi-Band also comprises the existing sight distances so that it could replace the conventional sight distance bands in vertical alignments according to RE (BMV 1985).

SUMMARY AND PROSPECTS

Unfavorable spatial road alignment can - although the element sequences of horizontal and vertical alignment fall within the permissible range – lead to errors in the central perspective illustration, cause the driver to misjudge the actual alignment and thus lead to unsuitable speed. Thus, spatial road alignment is an important criterion for road design; however, it is hardly taken into account in day-to-day design practice due to the lack of evaluation criteria. Due to the absence of technical progress, it is foreseeable that the minimum parameters of the design elements – despite increasing driving speeds – will be lowered even further. In this connection, spatial road alignment is increasingly gaining importance, especially in terms of stopping and overtaking sight distances.
Starting out from the fundamental principles of optical perception and the well-known theories of judging spatial road alignment, possible assessment criteria were derived from the phenomena of poor spatial road alignment and evaluated. The decisive criteria are sight distance, partial road disappearance from driver's view, sight distortion, sight quality and sight on changes in curvature. Therefore, visibility is considered the main criterion for the aspects of spatial road alignment to be assessed and encompasses the quantity and quality of sections which are visible to the driver as well as those invisible to him. Only two basic variables have to be determined for the evaluation: On the one hand, for every point of the roadway to be analyzed, it must be determined whether it is visible to the driver or not. If it is invisible, the depth below the corresponding outermost sight beam visible has to be calculated as well. Furthermore, for each target station, the visible roadway surface has to be calculated which – with reference to the comparable distance in the perspective image of an identical horizontal alignment with a flat vertical alignment and cross-section - subsequently results in the assessment value for the relatively visible roadway surface.
For this purpose, a procedure was developed with the help of which the required calculations could be carried out and their results represented in a graphic manner. On the one hand, the algorithm makes it possible to evaluate the existing stopping as well as overtaking sight distances according to their models as per RAS-L (FGSV 1995) via a simplified sight distance model with only one variable, and, on the other hand, to determine the depth of road disappearance for invisible points which is required for the quantitative assessment of diving, jumping and the hidden beginnings of curves. Subsequently, to evaluate sight distortion and sight quality, including the sag effect and warps, the relatively visible roadway surface is used as a criterion. The variables derived therefrom can be represented in a characteristics band (QuaSi-Band) which - similar to the well-known sight distance band - summarizes the relevant aspects of spatial road alignment in both traffic directions in a clear and objectively examinable manner.
The primary possible application of the QuaSi-Band lies in the evaluation of spatial road alignment, including a comprehensive visibility analysis within the context of the design procedure. It starts out at route determination with an inspection of the first horizontal and vertical alignments with a standard cross-section without information about the terrain and extends all the way up to a detailed analysis within the framework of detail designs with all the available cross section information. Furthermore, the existing network can henceforth also be evaluated in terms of spatial road alignment in order to render sections with an increased number of accidents less dangerous. The data on these existing roadways required for this purpose can, among other things, be recorded with high-speed measurement systems. Initial tests were already successfully concluded.
The new approach presented in this paper helps one to distance oneself from an optical evaluation of perspective images which inevitably merely results in a subjective evaluation and does not even take into account all the required aspects. Instead, one is led to embrace a mathematical and thus an objective evaluation. Since the derived evaluation criteria are based on theoretical observations and empirical values - perspective images were generated on the basis of artificial example alignments and quantitatively evaluated with regard to the shortcomings described in the guidelines - the methodology and assessment background must be verified and validated by means of more extensive research activities.

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