METHODOLOGY FOR CHECKING SHORTCOMINGS IN THE THREE-DIMENSIONAL ALIGNMENT

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ABSTRACT
Road design performed by highway planning authorities and planning offices is carried out at three separate levels: the horizontal and vertical projections and the cross-section. Experiments have shown that shortcomings in the 3D alignment may still occur when these three levels are processed separately and then superimposed. So it makes sense to calculate virtual perspective views and special control parameters using visualization tools and then use them to check the 3D alignment. Shortcomings of this kind can particularly cause accidents on two-lane rural roads. Unified model assumptions that match the driver's vision must be set to ensure the comparability of the central perspective views.

Drivers absorb images from a central perspective when driving along a road. So if a driver is unable to recognize a section of the road in the driving area ahead, this gives rise to blind sections. Designers need to use, as far as possible, standard three-dimensional elements. There are two major types of shortcomings: those that are safety-related and those that are merely esthetic.

A methodology has been developed to check the 3D alignment for shortcomings in the three basic stages (checking for standard 3D elements, safety-related shortcomings and esthetic shortcomings). By using the visualization tool "VISS ALL 3D", the design engineer can calculate the virtual perspective views with the safety-related shortcomings and can illustrate them in the blind section graph. Shortcomings in the 3D alignment must have been eliminated at the end of the redesigning process.

1. INTRODUCTION

The three-dimensional alignment of a road is obtained by superimposing the three design levels of the horizontal and vertical projections and the cross-section in traditional design methodology.

When traveling along a road, drivers perceive the three-dimensional alignment as a sequence of images of the road and derive their driving behavior from these, other senses (haptics) and their experience. If the driving area is clearly visible, drivers will select a suitable speed (1). But if the course of a road is not clearly visible due to crests or bends or if parts of the road cannot be seen, this can particularly lead to accidents with oncoming traffic on single-lane rural roads during passing maneuvers. As these kinds of problems in the three-dimensional alignment do not necessarily create accident black spots, they are not normally defined as faults, but as shortcomings. For this reason, they are often not recognized and eliminated.

Various approaches are possible in order to avoid shortcomings in three-dimensional alignment during the design process:

1. using qualitative rules, reference points and criteria,
2. using quantitative checking factors,
3. using combined qualitative assessment criteria and quantitative checking factors.

Extensive research work (2, 3, 4) has shown that a quantitative check is not universally effective. And a qualitative check alone often does not meet the needs because of the complexity involved – that is to say, a combined check should take place using both quantitative checking factors and qualitative assessment criteria.

2. RULES, REFERENCE POINTS AND CRITERIA

The following basic reference points are provided in the chapter on “Three-Dimensional Alignment” in the current standard work in Germany (RAS-L) for harmonizing the horizontal and vertical projections:

1. Points of inflection should be at roughly the same point on the horizontal and vertical projections and their number should be approximately identical. The following issues can play a crucial role:
   - optics: clearly recognizable changes in direction before the crest (at least 3.5 gon)
   - drainage issues: greatest longitudinal gradient at the zero point of the cross section
   - driving style: an easily recognizable and harmonious alignment
2. Tangent intersections for horizontal and vertical projection circular radii should be as close to each other as possible if the number of points of inflection is similar
3. The relationship between sag radii H_w and curve radii R has to be coordinated.
4. The relationship between the curve radius R and crest radius H_k should not be larger than 1/5 or 1/10
   - on a flat section: $H_K < H_W$ (good alignment optically)
   - on a hilly section: $H_K > H_W$ (to allow the greatest possible visibility)
5. Optical illusions (bulges, flat spots) or kinks should be avoided as far as possible.

Despite these rules, reference points and criteria, shortcomings in the three-dimensional alignment may still occur, even in designs prepared by experienced engineers, and they are often not discovered until after the road has been completed. Speed restrictions and bans on passing are then introduced subsequently.

3. CHECKING METHODOLOGY WITH QUANTITATIVE CHECKING FACTORS AND QUALITATIVE ASSESSMENT CRITERIA

3.1 General Issues

A research project has led to the development of a methodology for objectively checking the three-dimensional alignment (4). Quantitative checking factors from (5) are superimposed with information on driving behavior and are combined with qualitative assessment criteria, which are derived from perspective images. A distinction is made between

- safety-related shortcomings (critical blind spots and concealed starts of bend)
- design shortcomings (e.g. optical kinks on the horizontal and vertical projections).

While safety-related shortcomings must be eliminated by redesigning the vertical and/or horizontal projection, design shortcomings may be permissible in certain circumstances, if the expenditure on the redesigning work is too great or if it might clash with other design criteria. The redesigning work must not create any new shortcomings.

3.2 Principles

3.2.1 Standard Three-Dimensional Elements
By superimposing the horizontal and vertical projection elements in line with the rules, so-called standard three-dimensional elements (SRE) are created, the principles of which are described in (2). They occur if the beginning and end of bends on the horizontal projection coincides with the beginning of crests and sags on the vertical projection (FIGURE 1).

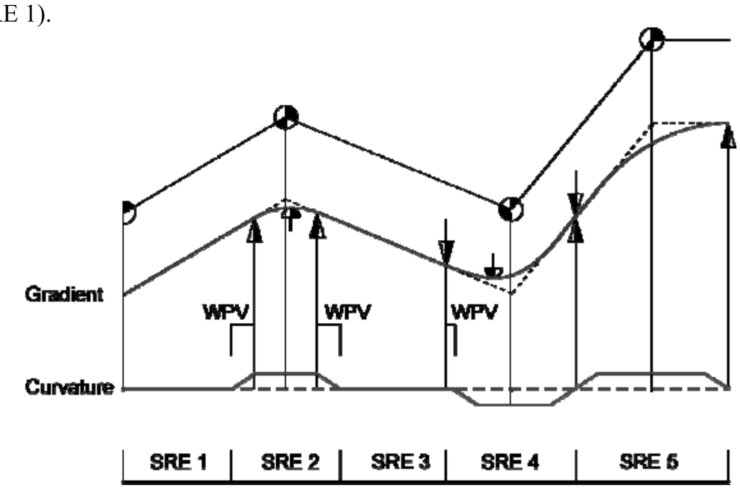


FIGURE 1 Standard sequence of three-dimensional elements (2).

Straights on the horizontal projection are treated as bends where R = ∞ and constant longitudinal gradients on the vertical projection are treated as if they were vertical radii where H = ∞. A sequence of standard three-dimensional elements alone exists if the beginning and end points on the horizontal and vertical projections are only slightly offset and the start of the bend is located in front of the start of the crest by at least the figures quoted in TABLE 1.

TABLE 1 Required displacement S[m] of the Start of a Crest behind the Start of a Bend in the Transition from Straight to Clothoid to Circular Arc (3).

Crest radius H [m]	Clothoid parameter A [m]			
	150	200	250	≥300
3000	25	50	65	80
4000	15	35	55	75
5000		25	50	70
6000		15	40	60
7000	No adjustment required		30	55
8000			20	45
9000			10	40
10000				30

These figures take into account the most unfavorable situation of a sequence involving a straight (with a constant longitudinal gradient) – a clothoid (with a crest vertical curve) – circular arc. Any approximate figures from a reversed arch provide almost the same figures.

The following standard three-dimensional elements are possible:

- a straight with a constant longitudinal gradient (even straight)
- straight sag
- straight crest
- bend with a constant longitudinal bend (even bend)
- curved sag
- curved crest

When processing the design on the horizontal and vertical projections, the design engineer should normally use the standard three-dimensional elements. This guarantees that no concealed starts of bends occur. The route that is designed in this way normally has far fewer other shortcomings in its three-dimensional alignment.

3.2.2 Normal Perspective

In order to be able to use perspective images for checking designs, the following unified specifications apply to calculating and preparing them (5):

- defined model assumptions
- the degree of detail
- coloring and contrast
- illumination model
- inserting locations, gradients and curvature graph

An assessment of whether the road traffic facilities are comprehensible is normally carried out from the driver's point of view (FIGURE 2).

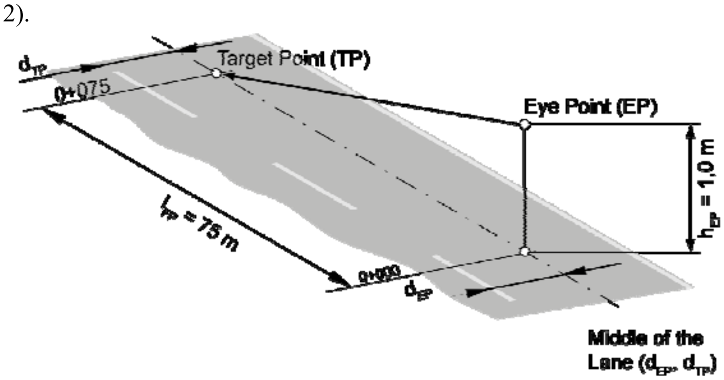


FIGURE 2 Model assumptions for the driver's perspective (4).

A digital terrain model forms the basis for the road design. If it had not been available during an earlier phase of the development work, an artificial terrain should be created to the right and left of the roadway so that a satisfactory optical effect is achieved.

The normal perspective that is developed (FIGURE 3) shows the curvature graph and the course of the gradient in addition to the locations on the header bar. This establishes a reference point between the perspective image, the location and any existing design elements. The display of the normal perspective and the defined model assumptions are provided by software manufacturers as the basic setting for calculating perspective images.

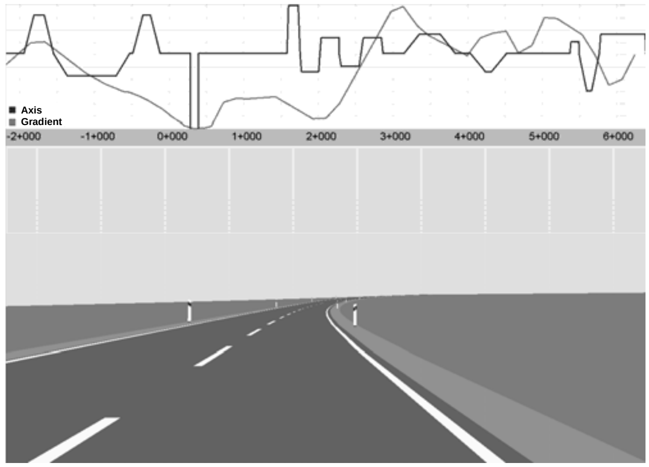


FIGURE 3 Normal perspective (4).

3.3 Safety-Related Shortcomings

3.3.1 Critical Blind Spots

The basics are developed from Zimmermann (6).

Blind spots occur if drivers (eye point height h_{EP} = 1 m) are unable to recognize a section of the edge of the carriageway in the area ahead. Blind spots are characterized by their depth s_d and their length s_l. A blind spot area is critical if the depth of the blind spot continues along a section measuring at least 75 m or is greater than 0.75 m. (FIGURE 4).

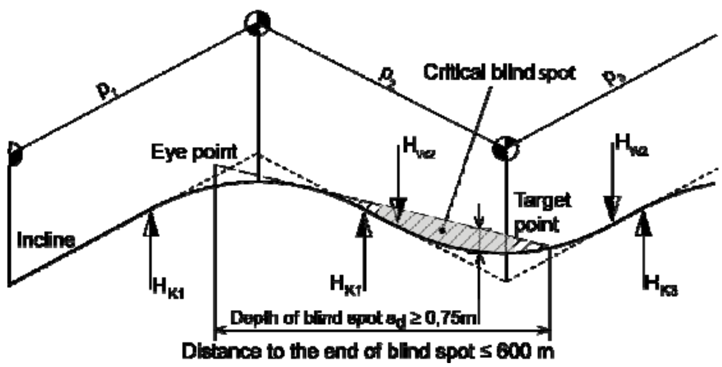


FIGURE 4 Definition of a critical blind spot (4).

Dips occur if a blind spot appears in a sequence of crests and sags where the direction of the route does not change (FIGURE 5). Dips may occur along straights or bends and deceive drivers about the course of the road, oncoming traffic or visibility.

Jumps occur if a blind spot appears in a sequence of crests and sags, where the direction of the road changes (FIGURE 5). This can lead to drivers failing to distinguish between a “disappearing point” and a “reappearance point” along the road. Jumps impair the visibility along a road and prevent drivers from seeing the course of the road ahead. Drivers may be misled about the course of the road, oncoming traffic and visibility.

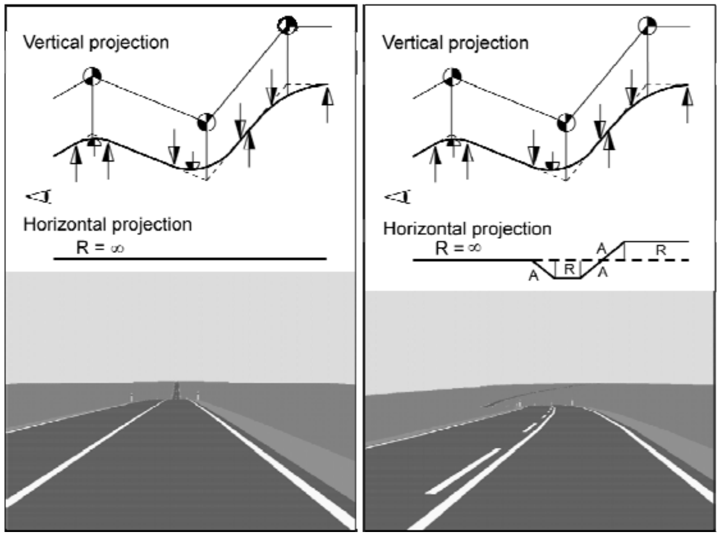


FIGURE 5 Dip and Jump (4).

3.3.2 Concealed Start of a Bend

A concealed start of a bend occurs if it is not possible for the driver to see the road surface ahead at least to the point where a change of direction of 3.5 gon (relevant change in direction) occurs on the horizontal projection at a distance of 75 m before the start of a bend (6). The start of a bend is recognizable, if the start of the part of the crest, which is invisible to the driver, is further away from the driver than the point of the relevant change of direction. In the case of large clothoid parameters (A ≥ 300 m), it is adequate if the clothoid can be seen for at least 100 m (FIGURE 6).

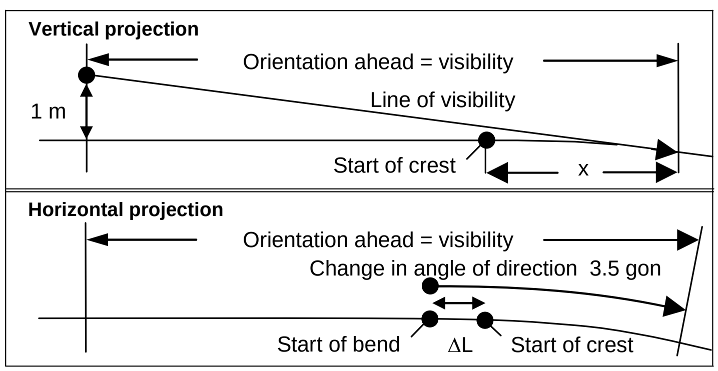


FIGURE 6 Model projection of a concealed start to a bend (4).

3.3.3 Blind Section Graph

In order to be able to better judge the safety-related shortcomings along a section of road, the results of the quantitative checking factors are shown in a characteristic graph – the blind section graph. Blind spots are normally calculated and displayed at location intervals of 20 m. Critical blind spots are recognizable along the graph if the blind spot depth s_d (thick vertical lines) is more than 0.75 m and is displayed for at least 3 locations (this means a distance measuring between 40 and 80 meters) and drivers can then see the road again no more than 600 m away. FIGURE 7 shows a critical blind spot area between locations 4+620 and 4+680 contrary to the direction of travel (lower blind section graph). Sections of the road, which cannot be recognized and where the blind spot depth is smaller than 0.75, are shown as light gray in order to mark the relevant threshold between visible and invisible areas for assessing the start of bends. The blind section graph shows the checking factors for both directions of travel (outward and return). The distance from the eye point is read off upwards for the direction of travel and downwards for the opposite direction.

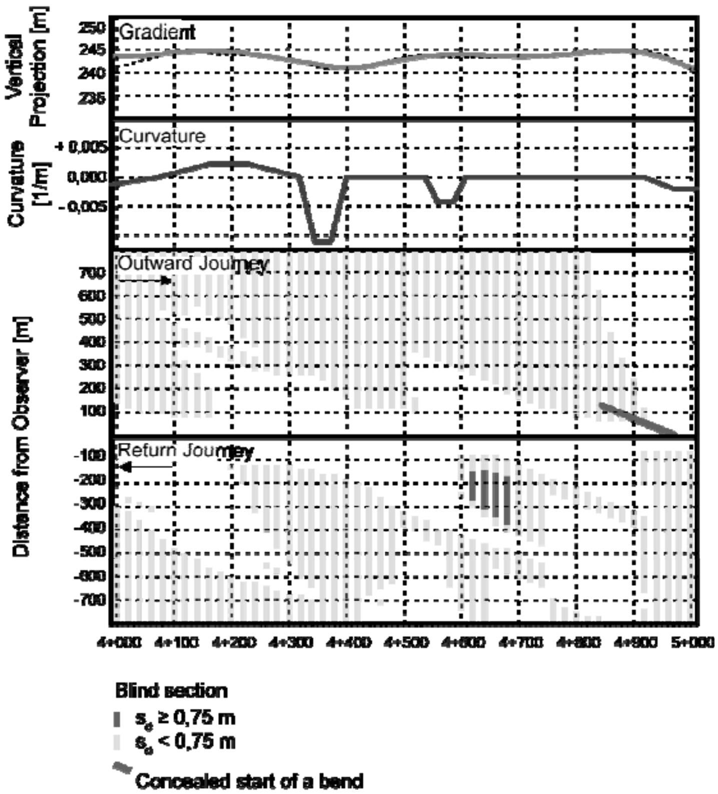


FIGURE 7 Blind section graph with a critical blind spot area and concealed start of a bend (6).

Concealed starts of bends are shown along the blind section graph by using a diagonally running thick line, which links the current distance to the point of the relevant change of direction (3.5 gon) for each eye point location. This line starts 75 m before the start of the bend and ends at the point of the relevant change in direction. FIGURE 7 shows a concealed start of a bend between location 4+840 and 4+960 in the direction of travel. 75 m before the start of the clothoid (approx. 4+920), the relevant change of direction of 3.5 gon (approx. 4+960) should be recognizable. But the road surface starts to be invisible at location 4+840 – the start of the light gray section on the color bar in the upper section (outward journey) – this is closer to the eye point than the diagonal line that is shown, which displays the current distance to the relevant change in direction. The line is not shown as a sign that the start of the bend can be adequately recognized if the point in the change in direction is closer to the eye point than the start of the road surface that is invisible.

3.4 Design Shortcomings

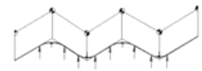
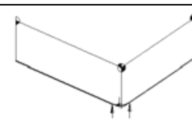
Design shortcomings in the three-dimensional alignment are not normally safety-related, but do have a general influence on the esthetics of the road design process. They also occur as a result of the superimposition process of the design levels and can only be recognized in qualitative terms using a perspective image at this stage. The most important design shortcomings are explained below (TABLE 2).

Judder occurs if the gradient follows brief elevations and is characterized by a fairly large number of changes in gradient with relatively low tangent lengths. This provides drivers with an uneven alignment and leads to uneven illumination of the road when driving in the dark.

Optical kinks in the road may occur if there is a bend with a relatively small radius and a slight arc length between two horizontal projection straights or if a sag with a relatively small vertical radius was designed on the vertical projection between two straights. The viewer's position has a huge influence on the effect, that is to say, optical kinks can particularly occur if the view ahead is large.

Bulges or flat spots are perceived optically if curved links going in the same direction on the vertical projection (crests or sags) are connected by two straights. This is often encountered on bridges with a constant longitudinal gradient.

TABLE 2 Design Shortcomings (5).

Design shortcoming	Causes in the alignment	Illustration
Judder	Short quadratic parabolas that follow each other in the vertical projection	
Optical kinks on the horizontal projection	Small rounding of radius between two straights in the horizontal projection	
Optical kinks on the vertical projection	Slight dip radius between two long straights in the vertical projection	
Bulge/Flat Spots	Short intermediate straight between two quadratic parabolas in the same direction in the vertical projection	

3.5 Checking Procedure

3.5.1 General Matters

The checks on the three-dimensional alignment for shortcomings take place using a three-stage checking procedure (FIGURE 8). While the checks for standard three-dimensional elements (working stage 1) and design shortcomings (working stage 3) are normally carried out manually and qualitatively, working stage 2 (checks for safety-related shortcomings) can take place numerically or quantitatively.

The starting point for the checking methodology (4) uses the existing calculations for the route with the help of a CAD program, where the axis data on the horizontal projection, the gradient on the vertical projection and the cross section data are all transferred to a digital 3D model and are combined with the terrain model. Any recognized shortcomings can be eliminated by altering the design elements on the horizontal and vertical projections using an iteration process.

3.5.2 Working Stage 1: Checking for the Results of Standard Three-Dimensional Elements

Working stage 1 tests whether the route that has been calculated consists of nothing but a sequence of standard three-dimensional elements. If this is the case, it is possible to proceed to working stage 2 immediately. But if there are some route sections without standard three-dimensional elements, checks can be made to see whether a sequence of standard three-dimensional elements can be created in the sections concerned by altering the design elements. If this is not possible, checks in working stage 2 can be continued separately for sections of the route with and without standard three-dimensional elements.

3.5.3 Working Stage 2: Checking for Safety-Related Shortcomings

As critical blind spots cannot be ruled out, even in a sequence of standard three-dimensional elements, the whole route is checked to see whether there are any safety-related shortcomings during working stage 2.

If the complete route consists only of a sequence of standard three-dimensional elements, it only needs to be checked for critical blind spots. If there are none, the checks can be continued with working stage 3. But if the whole route consists of sections with standard three-dimensional elements and sections without them (other sequences of elements), it is possible to adopt a different approach. While a check for critical blind spots is adequate for route sections with standard three-dimensional elements, route sections without three-dimensional elements are also checked to see whether there are any concealed starts to bends.

If any safety-related shortcomings are found, the design elements do not necessarily have to be altered if it can be proven by using perspective images that the further course of the road is still clearly recognizable for drivers.

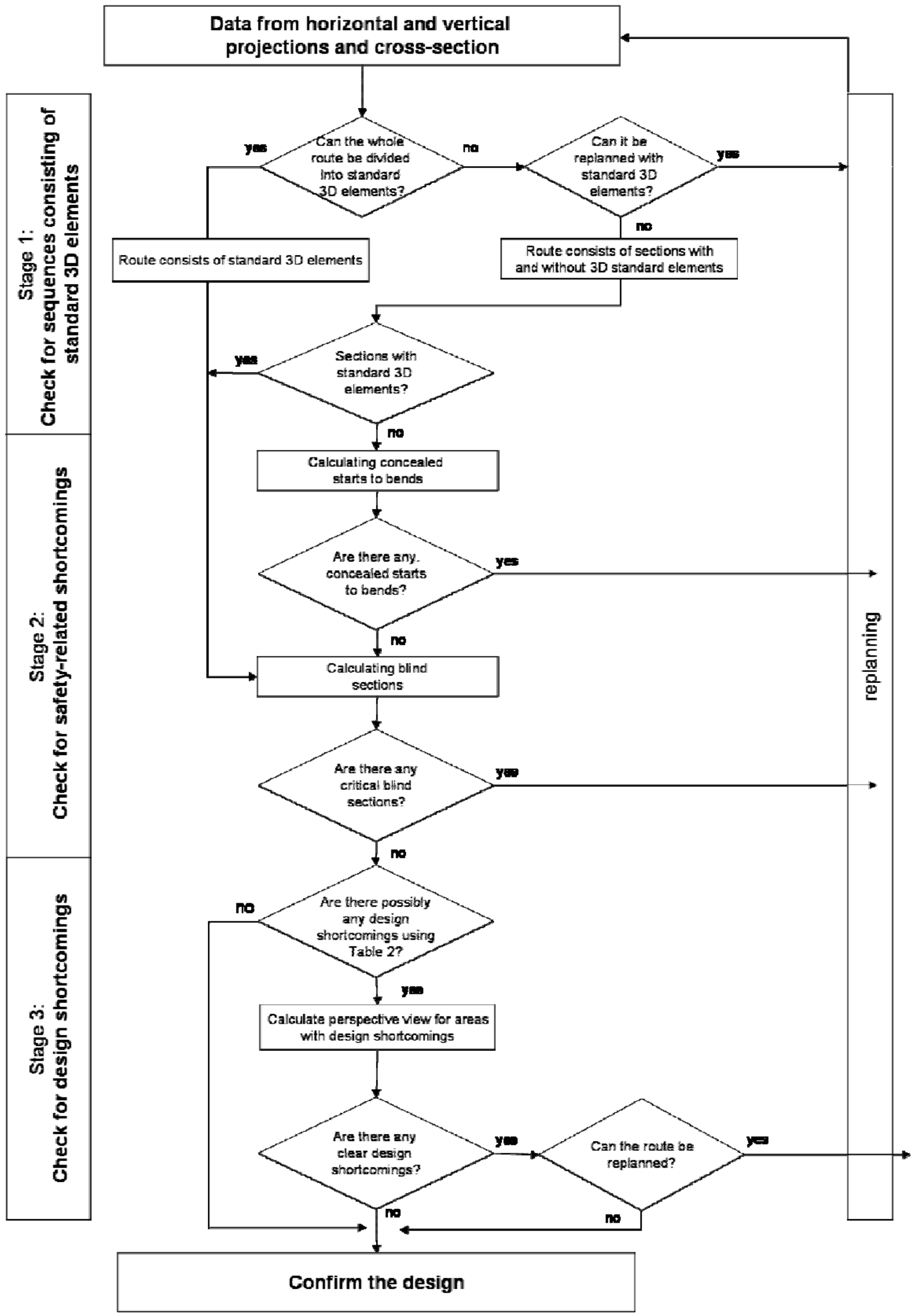


FIGURE 8 Checking process (5).

3.5.4 Working Stage 3: Checking for Design Shortcomings

Once all the safety-related shortcomings have been removed along the complete route in all the sections with standard three-dimensional elements and other sequences of elements, the final checks are made for any design shortcomings. The design engineer now has the task of checking the complete route for any possible design shortcomings. This qualitative process takes place on the basis of the causes that have been listed with the help of perspective images. If any design shortcomings have been recognized and can be corrected by keeping within the existing guidelines, the course of the road should be amended.

4. PRACTICAL EXAMPLE

4.1 Initial Route

The blind section graph (FIGURE 9) shows a concealed start of the bend shortcoming at location 1+850 (outward journey). There is a relevant change in direction point (3.5 gon) here. This point is 75 m from the actual start of the bend (looking ahead), so it is not visible from about location 1+725. This means that the ensuing course of the bend cannot be recognized by the driver.

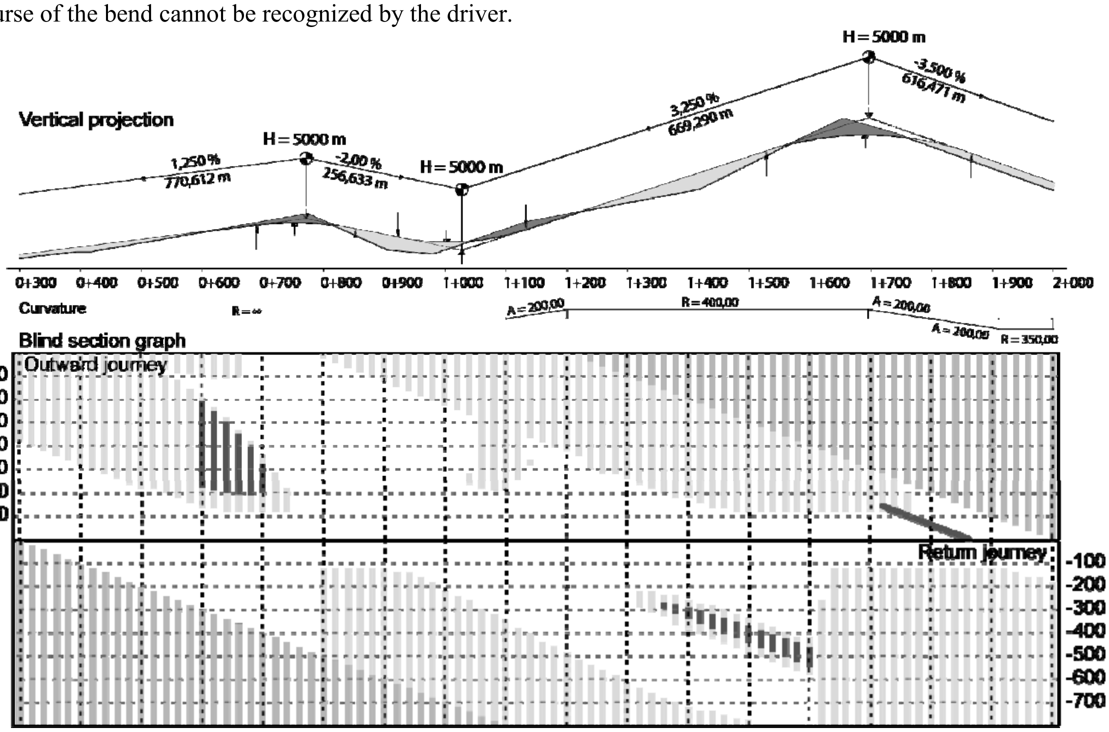


FIGURE 9 Blind section graph with critical blind spot area and concealed start of the bend (5).

The constellation of design elements between locations 0+800 and 1+200 also creates critical blind spots, which were detected from both directions (from location 0+600 on the outward journey or 1+600 on the return journey).

4.2 Redesigning Work

In order to eliminate the concealed start of the bend, the crest radius where H_K is 5,000 m was enlarged to H_K as 10.000m and 8.000 m on the vertical projection and the longitudinal gradient between location 0+770 and 1+030 was reduced to 0.50% and the first and second tangent intersection were moved. The blind section graph that is recalculated (FIGURE 10) now shows that the concealed start of the bend has disappeared, but the critical blind spots have still not been eliminated.

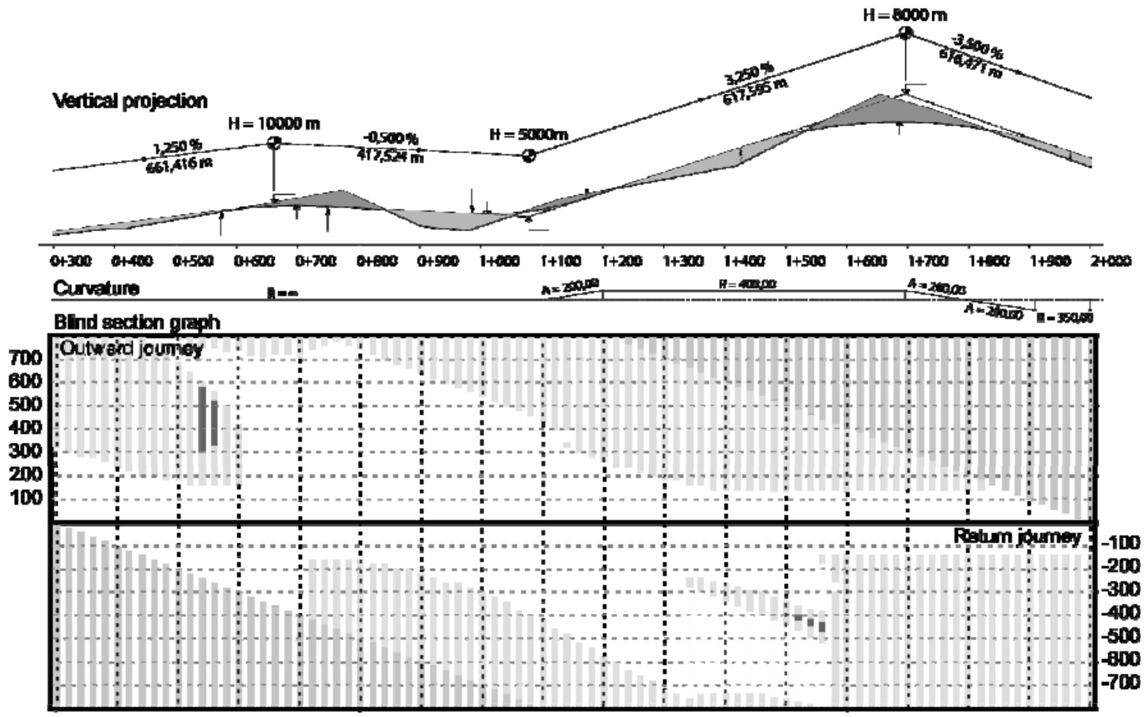


FIGURE 10 Blind section graph with critical blind spot area after the first redesigning stage (5).

In addition to the changes already successfully introduced, the tangent intersections were moved and the crest and sag radii were enlarged. The longitudinal gradients were changed once again in the critical blind spot areas and the tangent was shifted in order to primarily eliminate any obstruction in the driver's view as a result of the cutting at location 1+100 (return journey). The newly calculated blind section graph now reveals no more safety-related shortcomings (FIGURE 11).

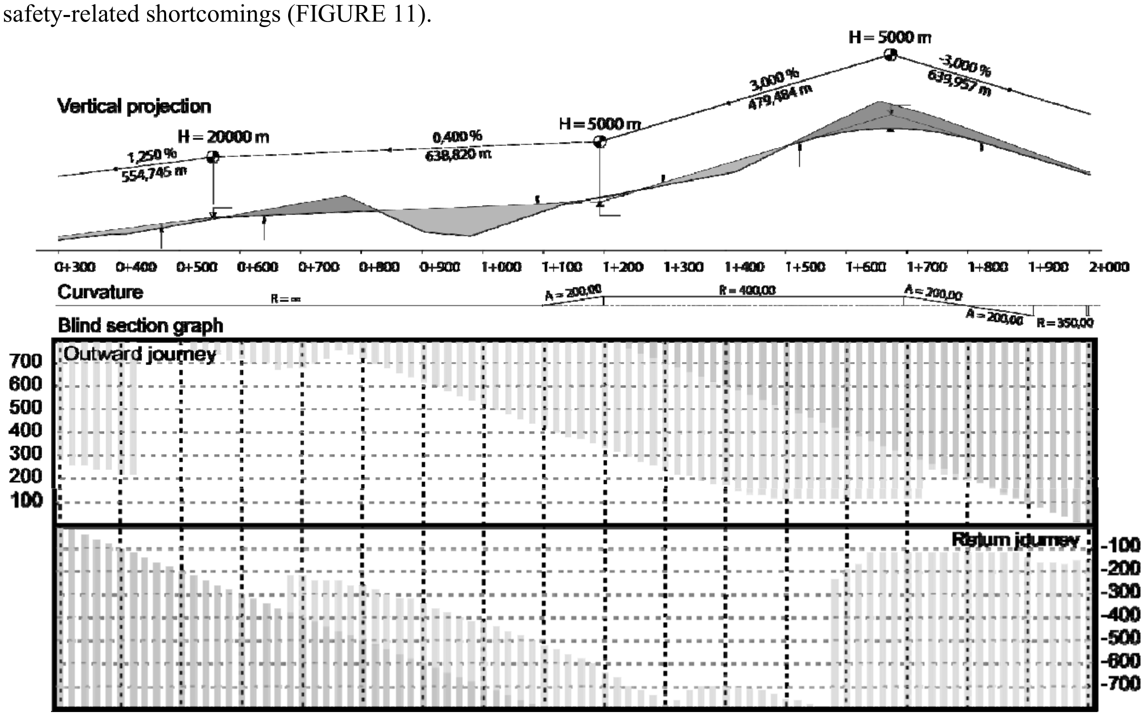


FIGURE 11 Blind section graph without safety-related shortcomings after the second redesigning stage (5).

The two redesigning stages clearly show that there are normally several correction options. The change to the crest radius and the mutual shifting of crest and bend are the most common used to eliminate the concealed start of a bend.

The critical blind spot areas as a result of the element constellation at location 1+000 show that it is basically necessary to view things from both directions. The elimination of the critical blind spots (occlusion by the road in the direction of travel, occlusion by the slope contrary to the direction of travel) normally requires several redesigning work stages.

5. CONCLUSION

The practical examples examined here clearly demonstrate that safety-related shortcomings (critical blind spots and concealed starts to bends) can be detected objectively and reliably by using the checking methodology that has been drawn up.

The relevance of existing shortcomings first has to be defined. Then all the safety-related shortcomings (and as many design shortcomings as possible) should be eliminated by redesigning the design elements on the vertical and horizontal projections.

It is sensible to first carry out redesigning work on the gradient. If this is unsuccessful, the axis in the area concerned should be changed. But there is no general procedure that fits every situation. This means that the design engineer must carry out the redesigning work as the overall situation demands.

By deliberately using standard three-dimensional elements, the number of shortcomings can be significantly reduced from the outset. Then concealed starts to bends do not occur.

By using the design elements as laid down in the guidelines on the horizontal and vertical projections, design shortcomings are the exception, not the rule. So particular attention should be paid to design shortcomings when designing thresholds, where extreme constraints occur or when checking existing routes.

The checking methodology (5) is being introduced into the standard guidelines in Germany – that is to say, the design engineer must carry out a check on the three-dimensional alignment for safety-related and design shortcomings during all design projects and eliminate them by carrying out redesigning work.

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