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A NEW METHODOLOGY FOR OPTIMIZATION OF THE GEOMETRIC HIGHWAY DESIGN PROCESS

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ABSTRACT

This paper concerns the interactive 3D alignment and visualization of roadways as part of a new methodology for the highway geometric design process. A basic concept of the step of pre-planning is presented based on an alternative but simple interpolation model to circumvent the disadvantages of conventional 2D pre-planning. It is shown that quality management of the geometric design process is supported with regard to several criteria of safety, economy and aesthetics. Optimization in terms of safety takes into consideration that there are complex relations between the road, the vehicle and also the driver. Several aspects of these relations are tested and validated during driving simulation which is supported optimally by 3D design proposed. A new work-place is proposed in order to integrate driving simulation into the design process without requiring much effort from engineers. Finally, the new methodology is compared to the conventional one. For this commercial tools as well as subjective ratings of long-standing experts in road design are considered.

Index Terms – 3D Geometric Design of Highways, Interactive Visualization, Splines, Driving Simulation

1. INTRODUCTION

The highway geometric design process is known to be complex and iterative. Besides considering the alignment of the road, transportation engineers are challenged with balancing of cost, performance, safety and aesthetic related aspects as well as dealing with operational, social and environmental impacts. Some of these aspects rely on manual and sometimes hand-sketched evaluations so engineers have a large degree of freedom and have to make more or less intuitive decisions whereby the quality and expenditure depends on the levels of experience and expertise of the geometric designer. Manual methods usually require dealing with a few or even only one particular aspect at a time and this modification of an almost complete design always leads to re-examine the draft. Thus several consecutive steps have to be passed iteratively to find a suitable variation.

This research focuses on the alignment design process of rural roads and highways and aims to utilize a new software approach to improve the design process.

1.1. Conventional Design

Traditionally, geometric design of roadways is a two-stage process in which the horizontal alignment is designed first and then the vertical alignment is defined based on the former [1].

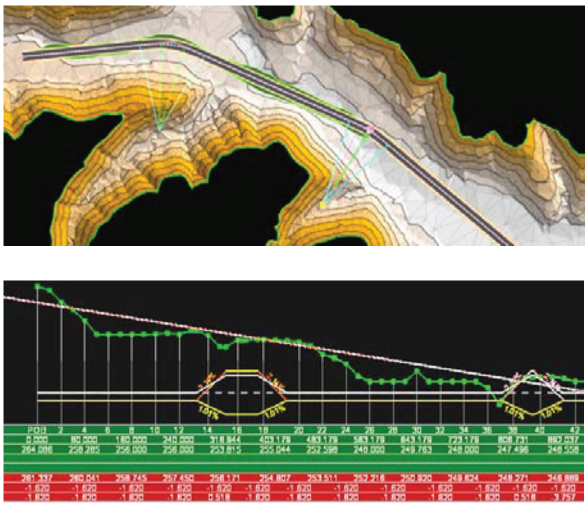

Figure 1 Interactive plan view (top) used for design of horizontal alignment and profile (bottom) showing elevation of road and terrain as well as curvature at stations of the track [2]

Separated processing of alignments in 2D plans prevents any corrections to be made in the road design for issues related to geometric inconsistencies or aesthetics since the three-dimensional representation of the road is not obtained until the superimposition of horizontal and vertical alignment in post-processing.

The perception of the given 3D scene including the digital terrain model and the surface of the roadway is very limited during the design process that is embankments and earth movement become visible very late, topography characteristics of the terrain and the fit of alignments in the landmark can be considered only slightly.

Unsuitable 3D alignments require backtracking to 2D layers.

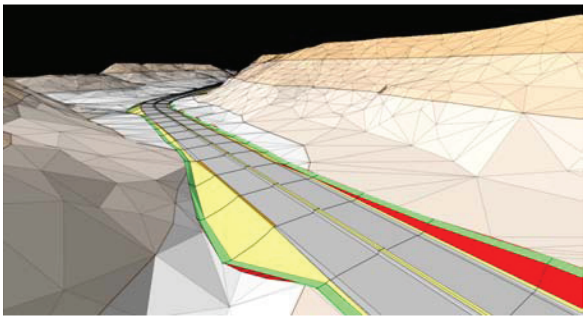

Figure 2 Perspective view of the digital terrain model, road surface and embankments without any possibilities for modifications [2]

Additionally this iterative process has to be passed in several levels of detail (five in Germany) beginning with the definition of a wide corridor in the phase of pre-planning up to the exact description of successive road elements in the final design. Each of these phases is concluded by a road safety audit and only the final one enables to obtain information about the characteristic of a road, earth movement, etc.

Further limitations derive from the interpolation model which is restricted to a sequence of three primitive geometric elements in the horizontal alignment (tangent, transitional curve, circular curve). The latter are required to fulfill the official rules for road design standardization but their concatenation can become costly depending on the length of track.

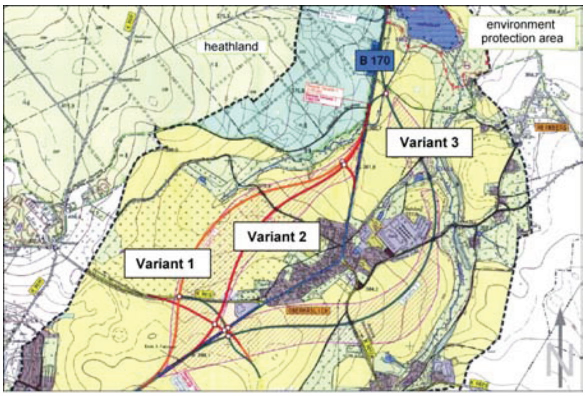

Figure 3 Variations of horizontal alignment to bypass a city [3]

Regarding to the addressed use case of rapid design of variations to bypass a town or the planning of long distance roads in context of urbanization the shortcomings mentioned above are determined and a new software approach is developed to assist the designer to achieve a final design more effectively.

2. REQUIREMENTS FOR THE INTERACTIVE 3D DESIGN PROCESS

The new approach for geometric design aims to reduce the two stage design process to a single stage process by presenting a 3D road surface with editable elements [1]. The engineer should be supported by tools that enable both the 3D alignment and appropriate visualization for interpretation of a design.

Therefore several requirements arise which can be categorized to be mandatory for the integrated concept of the new methodology, addressing usability aspects or affecting the design of the model.

2.1. Mandatory features

- Compatibility of the 3D alignment to traditional 2D layers and standard primitive road elements is required as an interface to conventional tools and to be compliant with rules of design standardization. That is the design must be exportable as standard primitive elements in format 040 (axis) and 021 (profile).
- Interactive graphical design and visualization in 3D with support of the new design workplace hardware (stereoscopic view, 3D input devices).
- Investigation on the usability of splines for the 3D alignment.
- Visualization of e.g. elevation (terrain, road), clearing and filling areas, slope or curvature as plot (formerly profile editor).

2.2. Severe model requirements

- Use of standard 3D elements to avoid shortcomings in the 3D alignment.
- Abstraction of details especially for bends like horizontal compound curves.
- Continuous connection of tangents and bends in position, direction and curvature.
- Compound curves should be supported – independent if recommended or necessary on local country regulations.

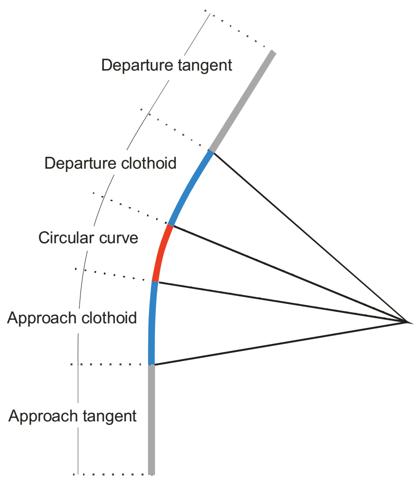

Figure 4 Compound curve containing transitional curves and circular curve to connect straight sections

- Curvature of symmetric compound curves – also those constructed using splines – should be shaped trapezoid like.

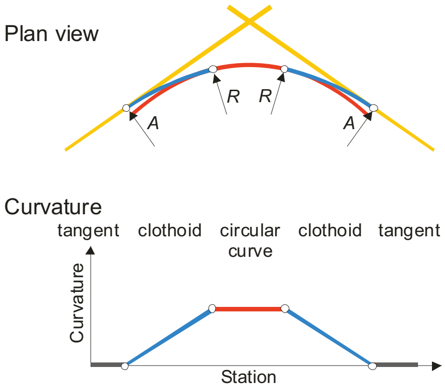

Figure 5 Plan view of compound curve and associated plot of curvature

- Local control on modifications.
- Explicit definition of tangents i.e. straight sections.
- Optional definable parameters for transitional and circular curves.
- Interface for online safety analysis of a design.

2.3. Usability demands

- Intuitive and convenient operation of the 3D design close to conventional design methods.
- Online safety analysis of the horizontal alignment to avoid safety hazards and assure design consistency.

2.4. Particular requirements

- Earth movement respectively filling and clearing areas should be visualized in 3D.

Referring to the requirements of the interactive graphical design it is obvious that standard primitive road design elements should be either used directly or be convertible to be very close to the final design even in the step of pre planning.

Whilst focus is on 3D alignment no consideration is taken about intersections, roundabouts or sectioning.

3. GEOMETRIC DESIGN

3.1. Design methods and proceedings

Traditionally there are four methods of manual geometric design while their use depends on the terrain if it is mountainous, rolling or flat and chosen also by the geometric designer's level of skill.

The tangent based approach is evaluated as intuitive by long time experts and supported by most conventional design tools.

Tangents in the plan view are used to roughly define the axis while control points are approximated by bends which can be modelled using Bézier curves. Even if the shape of the control polygon and the curve are very similar the alignment of the road is only in the convex hull of the corresponding control polygon [4]. Nevertheless this approach was adapted to 3D in earlier researches. To circumvent that the position of a single control point affects all points of the curve and to be more accurate piecewise straights and Bézier curves were applied. That is the explicit definition of straight sections on tangents and bends only to connect straight sections.

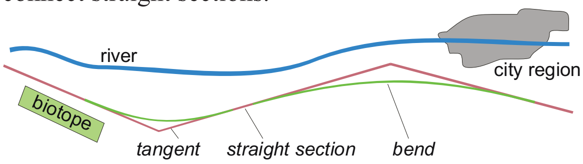

Figure 6 Tangent based approach for horizontal alignment design

By the use of road design software other attempts became applicable for example the interpolation of control points by a spline that is defining control points on a given terrain through which the roadway passes and finding suitable tangent lines that connect these points. Anyhow the use of a free interpolating spline is limited because the decomposition into standard primitive road design elements is estimated not to be trivial and modification of a single control point affects neighbouring sections thus avoiding local control.

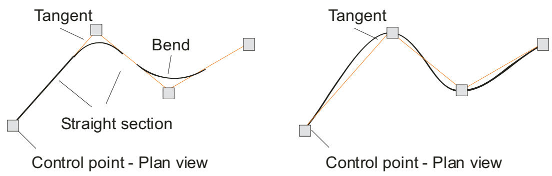

Figure 7 Approximation (left) and interpolation (right) of control points in the horizontal alignment

The most important limitation of the interpolating model is the complexity in case of decomposition to standard primitive road design elements since no straight sections are explicitly defined.

3.2. Model for 3D alignment

Because of the former evaluation the tangent based approach in conjunction with explicit description of straight sections is used for the horizontal alignment. In contrast to earlier researches [1] the control points of the control polygon are not located in 3D but positioned only two dimensional in the horizontal plane. Separated models are applied to describe the axis and the profile to simplify the process of decomposition into standard elements used as an interface to conventional road design software and to be compliant to the rules of design standardisation.

The superimposition of the 2D layers takes place in a facade which aggregates axis and profile to enable 3D visualization, implementation of 3D design elements, ensure consistency of underlying models as well as delegate user input to the appropriate layers. The implementation of 3D design elements is recommended for issues related to safety, drainage and driving dynamics and is accomplished by associating control points of the gradient to primitives of the axis.

The logical structure of the software system is illustrated in the following diagram. The model contains a control polygon of the 3D alignment which is internally projected to the control polygon of the axis in the x-, z-layer and gradient control points set to stations of the axis.

Modifications of the 3D alignment based on changes of graphical handles are subject to interact with the facade by a controller layer. The facade itself assures internal consistency of axis and profile.

The view components are interactively rendering the 3D scene including terrain, road surface and handles for editable entities as well as printing plots for station depended properties like elevation, curvature, slope and so on.

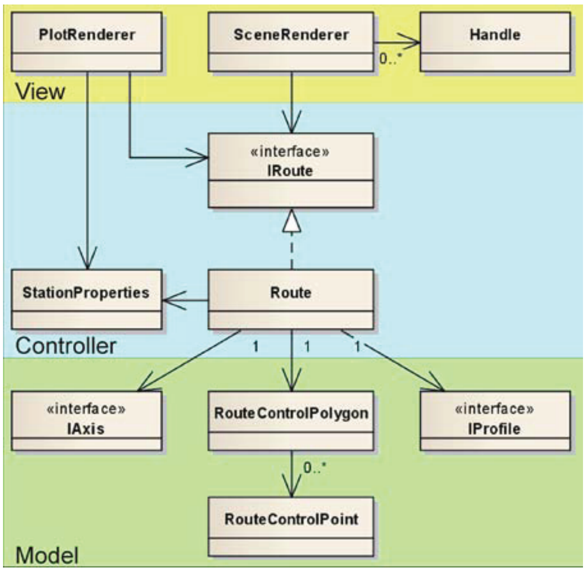

Figure 8 Logical model of the software system

3.3. Horizontal Alignment – Axis

The control polygon of the axis is defined by control points and connecting tangents in a 2D layer. Each of the tangents contains a straight section whereby both the control points of the tangent and the start and end of straights are editable entities. Straights of zero length are designable. The decision to provide straight section boundaries editable instead of the center of bends is accounted by the possibility of the design of asymmetric curves.

For reasons of convenience of the graphical design the horizontal alignment can be modified manifold. Hence it is possible to translate control points or change bends radii while affected elements will be rearranged or operations snap to boundaries.

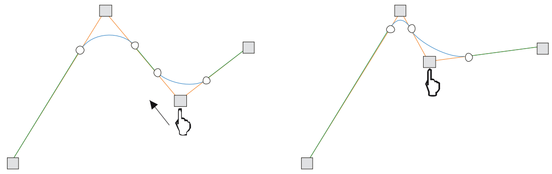

Figure 9 Modification of the control polygon is treated by the model of the axis

The consistency of the horizontal alignment can be validated by the use of special property disclosure of road elements. The type of element, it's length and position on track, maximum curvature and other properties can be determined. This interface is designed for automatic evaluation of the relation between successive road elements (speed difference of road segments and transition) in further work since design consistency is estimated as an important highway geometric feature affecting traffic safety. Generally speaking, the smaller the difference of alignment features between successive road segments the better the alignment consistency is and the better the highway safety is [6].

Bends are implemented using Bézier curves connecting straight sections. In earlier researches [1] piecewise polynominal equations of 4th degree were investigated but raising to 5th degree enables to control the curvature at the start and at the end of the curve independently. In the current model the curvature on the boundaries needs to be zero to continuously connect to straight sections.

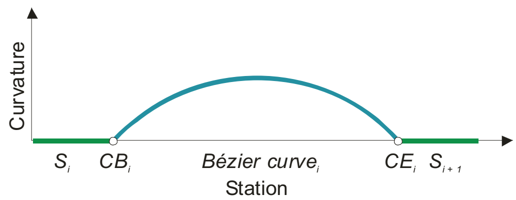

Figure 10 Curvature of a Bézier curve of 5th degree using three collinear points on both ends to achieve zero curvature

It is also necessary to achieve a trapezoid shaped curvature that is a constant curvature for circular curve length and clothoids (transitional curves) at the beginning and at the end.

For this reason some investigation on shaping of the control polygon has taken place. The parameters g1 and g2 describe the relative position of control points on the tangents. Depending on the angle between tangents and the desired circular curve length their values were determined and are applied automatically.

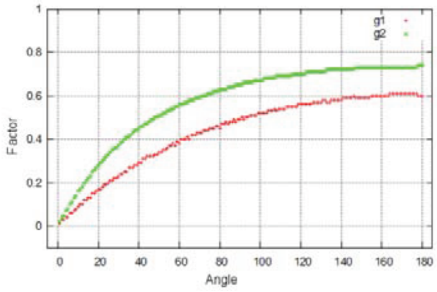

Figure 11 g1and g2 depending on enclosed angle between tangents for circular curve taking up one third of compound curve length

The application of g1 and g2 to locate the control points of the Bézier curve results in a nearly trapezoid shaped curvature.

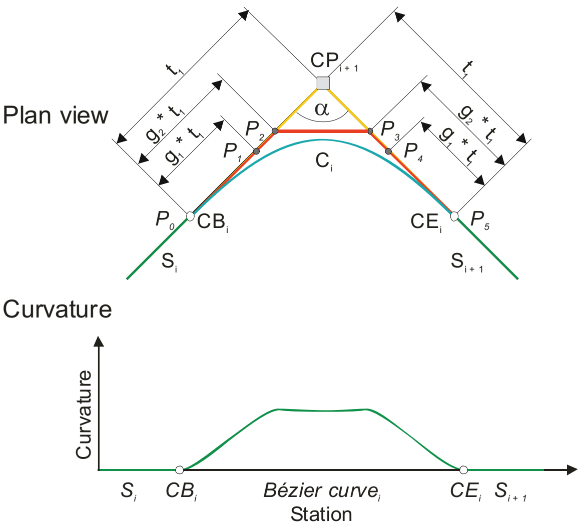

Figure 12 Fifth degree Bézier curve and curvature

3.4. Vertical alignment – Profile

The gradient is independent from the axis and it's implementation is based on the conventional model. That is because a fully 3D spline based model bears a major disadvantage. The variation of speed in the algorithm to determine curve points along the axis leads to an undesired progression of spot height in the profile.

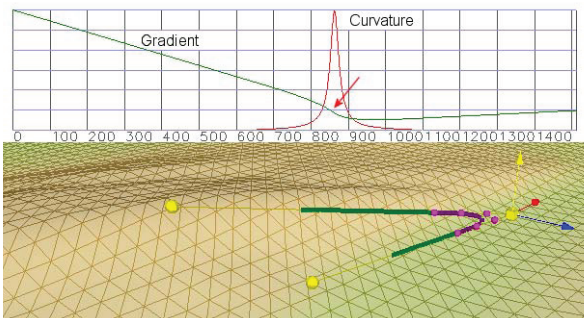

Figure 13 Unfavorable profile on low angle bends

Because of large radii on crest and sag vertical curves there is no need for transitional elements and the internal radius is calculated by the use of parabolas. Defined elements in this model are control points that are set to a position on the axis and their properties are elevation and radius.

The linkage to horizontal alignment elements is due to the demand for 3D design elements and is illustrated in the picture below.

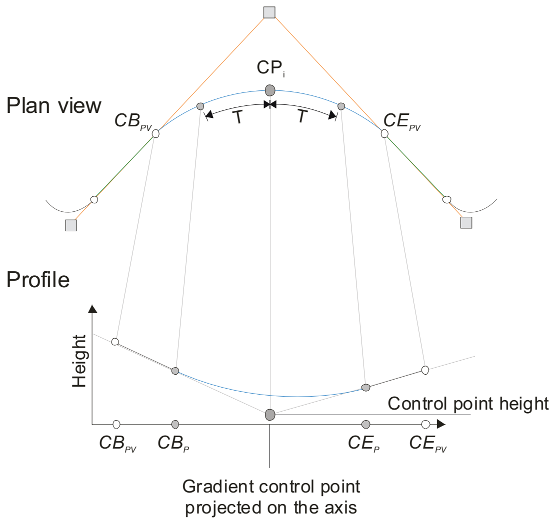

Figure 14 Linkage of gradient control points and vertical curves to the horizontal alignment

The length of the vertical curve is relative to the length of the bend in horizontal alignment. This is implemented to facilitate drivers to assess direction and curvature of bends before slope. Equal to the configurable behavior of the axis this model also contains convenience methods to shift adjacent sections or snap to section boundaries while keeping the profile consistent.

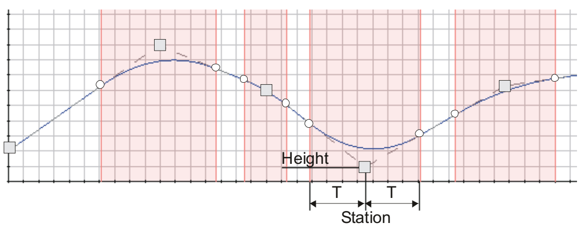

Figure 15 Image section of gradient covering six control points. Linear slope at the beginning and at the end (not shown), parabola internal radii

Although currently the gradient is coupled to the horizontal alignment the underlying model can be detached and used separately to establish appropriate road design in rolling terrain. That is vertical profile control points exists independently from horizontal elements and are associated with positions on the axis only. Not elaborated yet is the adjustment of gradient in the scenario of stretching particular horizontal road sections.

4. NEW METHODOLOGY OF HIGHWAY GEOMETRIC DESIGN

The basic concept of the new methodology is to look at the interactive 3D alignment and visualization as only one step in the process of highway geometric design. When the alignment is almost complete an approximation of the standard primitive geometric elements typically representing horizontal compound curves, straight sections and profile is automatically exported which can be processed in further steps. This is fine-tuning elements to be more close to the final design as well as geometric safety analysis both by the use of conventional road design tools. Interactive 3D design process is also completed by validations by means of driving simulation, recording and subsequent analysis to determine design inconsistencies which could pose safety hazards or deleterious effects.

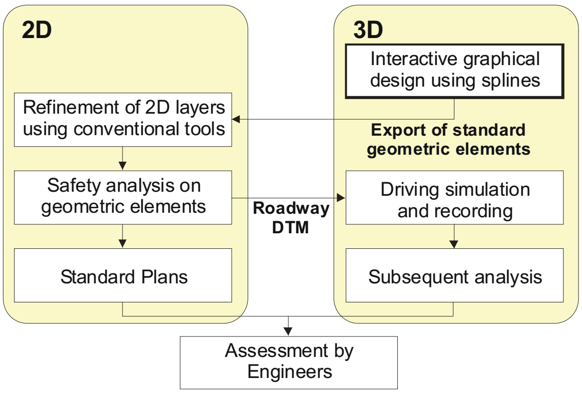

Figure 16 Steps of the new methodology for highway geometric design

The analysis is carried out by a team of qualified experts identifying potential safety risks, assessing the safety performance of the projected highway and proposing recommendations for improvement [7].

A new design workplace is proposed in order to integrate driving simulation into the design process without requiring much effort from engineers.

Figure 17 Prototype of a new design workplace in the scenario of driving simulation

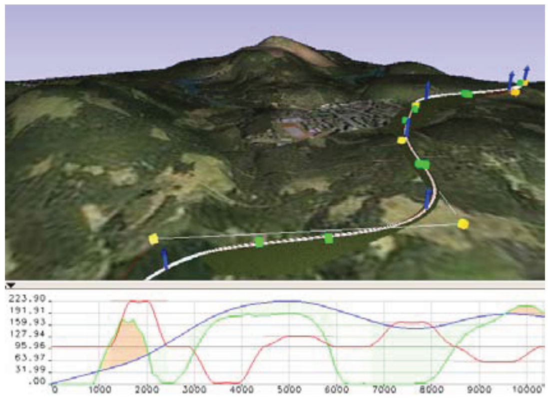

Figure 18 Screenshot of prototype software showing interactive 3D alignment process (top) and visualization of plots of elevation, curvature (bottom)

5. CONCLUSION AND FURTHER WORK

This paper outlines how geometric highway design can be processed interactively in 3D. The applied model is based on conventional separated layers for horizontal and vertical alignment which are superimposed by a special facade that enables real-time 3D visualization as well as processing input of 3D manipulation to control the appropriate underlying models. The usability of Bézier curves to simplify the design of horizontal compound curves is shown and can be estimated to be advantageously compared to standard primitive elements in the design of complex alignments. The influence of the Bézier curves' approximated trapezoid curvature on driving behavior is currently not validated. The implemented decomposition to standard primitive design elements and the ability to encapsulate these by meta objects in real time leads to the conclusion that both models – standard primitives and spline – are equally effective useable in the proposed 3D design process.

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