National Technical University of Athens
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Doctoral Dissertation

CONTRIBUTION TO THE INVESTIGATION OF STOPPING SIGHT DISTANCE IN THREE-DIMENSIONAL SPACE

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Extended Summary

The issue of road safety assessment has always been the case in road design. Sight distance is a measurable parameter which can be a key criterion in road safety assessment considering the human factor. **Stopping Sight Distance (SSD) adequacy**, namely ensuring sufficient free length in the front view of the driver in order for him to be able to perceive and react to dangerous situations, **is a basic requirement for the safety of traffic flow**. The required SSD, which relates to the ability to bring the vehicle to a halt, depends on road geometry, the driver's perception – reaction ability and the vehicle's dynamic features, while it is the basis for selecting critical geometric parameters. The available SSD mainly depends on road environment and road geometry. **Therefore, it is important that SSD adequacy investigation is performed across the entire road, in relation with the features of the road environment**.

The objective of this Doctoral Thesis is the development of a methodology for SSD adequacy investigation, considering concurrently the factors which impact a road's provided safety, namely the road geometry, the vehicle and the user – driver. The proposed methodology includes considering the involved parameters in three-dimensional space and the identification of areas where the sightline between the driver's eyes and an obstacle is interrupted by an obstacle which is positioned in such way so that the road's security is compromised. More specifically, the proposed methodology relates to the following:

- As far as the **road's geometry** is concerned, the influence of roadside features is investigated, in addition to the three-dimensional consideration of the design parameters.
- Regarding the **vehicle**, the influence of its dynamic features during its movement along a curved path is taken into account and, therefore, a more accurate simulation of the braking process in a three-dimensional rolling surface is given, since this is related directly to the road's geometry.
- The presence of the **user – driver** is taken into account in the sense of the ability to perceive the alignment from the driving position, through the visualisation of the road and the surrounding environment.

In the current design practice of assessing visibility conditions, the road's geometry is not fully taken into account, given that consideration of the road environment is rather simplified and fragmentary, in a two-dimensional space. SSD adequacy investigation is mainly based on two-dimensional models, which means that check is performed independently on the horizontal alignment and the longitudinal profile. The models of assessing SSD adequacy and determining critical geometric quantities to be adopted in the design of horizontal alignment and longitudinal profile are similar and basically only differ in the selection of their parameters. Consequently, there are parameters which are not taken into consideration and their effect can be crucial in the safety provided.

More specifically, during the assessment based on the horizontal alignment, critical parameters such as variable longitudinal slope due to the presence of a crest or sag curve, and the heights of the driver's eyes and the obstacle are ignored. Similarly, assessment based on the longitudinal profile is performed assuming that the horizontal alignment is straight, which obviously applies to individual cases, while the influence of the transverse slope of the roadway is also important. Additionally, vehicles are regarded as material points without taking into account their dynamic features, thus the correlation of their parameters with road safety is empirical. **Therefore, the proposals for ensuring SSD adequacy, through the selection of critical parameters for the combined design of horizontal and vertical geometry, are mainly given in the form of empirical recommendations, with insufficient scientific documentation**.

In addition, guidelines for road design provide mathematical formulae for calculating SSD in simple independent horizontal and vertical alignments, **with the use of simplifying assumptions which, however, not fully correspond to reality**, with chances of providing false results. For more complex cases, the use of graphical or three-dimensional methods is recommended, **but no further description is given**. Moreover, it is proposed that perspective images of the road can be created in certain positions and the need of three-dimensional analysis is emphasised.

Therefore, the current two-dimensional design methods may overestimate or underestimate available sight distance, leading to unnecessary increase in costs or, even worse, to the existence of dangerous sections along a road. In such cases, the effects can be detrimental to the cost and efficiency of existing and planned roads, given that excessive modifications and/or areas with speed limits less than those truly required are rather inevitable, which may not meet the driver's expectations and compromise design consistency.

Given that SSD adequacy is of fundamental importance for the safety of any road, **extensive research has been carried out, in determining both the required and available SSD**. The proposed methods for determining sight distance can be divided into two-dimensional (separate analysis of horizontal and vertical alignment) and three-dimensional (road is considered directly in space), as well as into graphical and analytical. As far as two-dimensional approach is concerned, methods aiming at a more precise approach of SSD assessment, in comparison with the existing road design guidelines, have been published. Furthermore, various three-dimensional methods have been developed for SSD adequacy investigation, which take into account the interaction of the elements of horizontal and vertical geometry, as well as the road environment, and thus allow for a more realistic and accurate analysis.

According to the two-dimensional method, the available SSD is calculated by considering exclusively either the horizontal alignment or the longitudinal profile. **The**

problem arising in cases of independent consideration of either the horizontal or the vertical profile, is the possible inaccuracy of the results of calculation, since the interaction between profiles is not taken into account in the driver's perception of the road environment, especially in cases of simultaneous existence of curvature. An improvement to this approach is SSD calculation on both profiles and the adoption of the minimum value in each position of the road, as a conservative estimate. However, the results are still approximate. **Therefore, two-dimensional design can overestimate or underestimate SSD available, with negative effects on the economy and, especially, on the safety of the road**.

As far as three-dimensional graphical methods are concerned, they represent an alternative way for SSD analysis and allow for a correct approach to the SSD problem. **However, graphical methods prove to be time consuming, since they do not offer an automation of visibility analysis** and, hence, they are not considered effective if used in large scale road projects.

Therefore, it is obvious that three-dimensional analysis, with the use of analytical models, allows for the most appropriate approach to the issue of visibility, where the road is considered as a single entity in space, so that all of its features can be simultaneously taken into account. Additionally, the creation of perspective images from the driver's position, along the road, is a useful tool for checking the alignment's quality and for detecting problematic sections in terms of visibility.

The proposed three-dimensional methods of SSD assessment allow for an accurate simulation of a compound road environment and, hence, the accurate determination of the driver's actual field of vision. **However, most of these studies focus on the optimisation of the available SSD either by introducing new algorithms or by proposing certain combinations of design parameters, ignoring in many cases some of the elements of the road and its environment, which significantly affect visibility levels**. Furthermore, none of these approaches has suggested a comprehensive methodology to concurrently simulate from a three-dimensional perspective both the cross-section elements and the vehicle dynamics in space during emergency braking conditions. Finally, another key deficiency of the related three-dimensional methods is the lack of analysis of the design elements limiting the available SSD in each case, which would allow the designer to immediately perform the necessary adjustments to further improve the end result of the alignment.

The proposed three-dimensional analytical method has been developed in order to create a comprehensive visibility analysis tool, which will provide fast and accurate results, minimising the deficiencies identified both in relevant methods and in current practice. This method is incorporated in the "H12" road design software, which, similarly, has been developed by the author of the present Doctoral Thesis and provides the ability to perform all tasks related to the geometric design of a road. The proposed methodology is summarised as follows:

- **A three-dimensional model of the road and the roadside area is created**. With the use of **"roadlines"** it is possible for the driver's eye and the obstacle to be placed laterally and at any distance from the road axis, as well as for visibility levels to be specified, due to the existence of road components and equipment, which constitute potential sight obstacles. Next, a total number of road cross-sections is produced, depending on the calculations step which is defined. With the use of **triangulation** method, a network of triangles is created among the cross-sections, representing the road and formations surfaces, as well as the Digital Terrain Model of the area. The final road and roadside model is derived by the superimposition of the road model to the terrain model.
- **Demanded SSD is specified**. Demanded SSD calculation is based on an improved approach to the current practice, where both horizontal and vertical curvature are considered, by the inclusion of the influence of transversal and longitudinal friction, as well as the variable inclination along crest and sag curves.
- **Available SSD is specified**. Available SSD calculation is based on the identification of potential points of intersection between the sightlines amid the driver's eye and the obstacle, and the triangles representing road and roadside surfaces. The equations of triangles and sightlines, as well as their points of intersection, are determined using analytical geometry.
- **SSD adequacy assessment is performed through an iterative algorithm**, so as to identify areas along the road where sightlines are interrupted by an obstacle and their length is less than the required SSD. The precision of calculations depends on the calculations step, namely the distance between two consecutive points along the road under consideration.
- **The results of analysis are exported in the form of diagrams displaying available and required SSD**, namely:
  - Demanded SSD diagram.
  - Available SSD diagram, as it has been calculated using the three-dimensional analytical method.
  - Available SSD diagram, as it has been calculated based on the longitudinal profile of the road (two-dimensional method).
  - Three-dimensional extension of the visibility diagram, through which the visibility conditions on the remaining part of the road are described, for each point of the road.
- **Perspective images from the driver's position are created**, along the road, according to the parameters entered.

With the use of the H12 software, the proposed methodology is applied to two examples of SSD analysis, in order, firstly, to examine **to what extent the use of marginal proposed values of design parameters, according to road design guidelines, provides SSD adequacy** and, secondly, **to compare the corresponding results obtained by applying the two-dimensional method (where only longitudinal profile is taken into account) and the proposed three-dimensional analytical method**. Two theoretical alignments are considered, with different typical cross-sections, whose horizontal alignment and longitudinal profile are of the same form, so that every possible combination of simultaneous curvature appears. Marginally allowable values of the design parameters are used, according to the Greek and German road design guidelines.

The study of visibility diagrams shows that, **in divided roads, the results of the two alternative methods vary greatly, although it is shown via both of them that the available SSD is significantly restricted in areas with crest vertical curves. In undivided roads, the corresponding results are similar in cases of crest vertical curves, where it is shown that available SSD is significantly restricted, and differ in cases of sag vertical curves, where, according to the three-dimensional method, available SSD is significantly restricted.**

These results confirm the conclusions of similar researches, namely that **the two-dimensional method may lead to incorrect results concerning the available SSD**. This method is not entirely reliable, given that, on the one hand, the horizontal alignment is considered straight and, on the other hand, only the road axis is considered and therefore cross-sectional elements are not taken into account, although they greatly affect visibility conditions. As far as road safety in relation to the available SSD is concerned, it is concluded that **design using marginal values of the alignment parameters, as they are given in road design guidelines, entails the existence of inadequate SSD**.

The key factors that may reduce or even lead to insufficient available SSD are the following:

- **The median safety barrier, in cases of motorways, in left-turn horizontal curves overlapped with crest vertical curves**, especially in the overtaking (inner) lane. Restriction of the available SSD is caused due to the short lateral distance of the driver from the safety barrier, combined with the form of the alignment. Similarly, SSD shortage may occur in case of a tunnel, where the lateral distance of the driver from the sidewall is about the same as the corresponding distance from the median safety barrier.
- **The traffic barrier on either side of the road and the cut slopes**, mainly in cases of undivided roads with one travelling lane per direction. The problem becomes more pronounced as the lateral distance between the driver and the side obstacle is reduced, therefore more critical are the cases of roads with smaller widths of traffic areas and even more in cases of right-turn horizontal curves overlapped with crest vertical curves.
- **The width of outer shoulder in cases of cut slopes**. It is obvious that the problem intensifies in cases of small width shoulders (mainly on existing roads), vertical walls in areas of technical works etc.

The proposed methodology constitutes a comprehensive approach to simulate simultaneously both the cross-section elements and the dynamics of vehicle movement during emergency braking situations, taking into account the elements of the road and its environment that affect visibility levels. The approach of SSD problem is made in the three-dimensional space, in the sense that both the road and its environment are treated as a whole, as opposed to the usual practice of SSD analysis. The main advantages of the proposed methodology include:

- The procedure of entering the required parameters and creating the three-dimensional road and roadside model is **simple, fast and reliable**, giving the designer **the possibility to explore the influence of a large number of factors involved in SSD assessment**.
- All the road elements and features are represented **in a realistic way**.
- The proposed approach for determining the available SSD, through analytical equations, is **flexible and efficient**.
- It is indicated, at each position along the road, **the cause that leads to restricted or insufficient SSD**, therefore corrective adjustments can be immediately made by the designer.
- The three-dimensional extension of the visibility diagram provides the possibility to evaluate, in every position, **the road length in front of the driver that is visible and the SSD deficiency**, as well as the cause of SSD restriction in positions where SSD is insufficient.
- With the use of perspective images created along the road, **the quality check of the three-dimensional alignment can be carried out and also SSD assessment can be performed directly**, without the use of visibility diagrams.

This methodology can be applied to **any road environment in which SSD assessment is required**, while its accuracy is variable and is selected by the designer, depending on the importance and the design stage of the road under consideration.

Keywords: Stopping Sight Distance (SSD), Road Design Software, Three-Dimensional (3-D) Alignment, Design Consistency, Road Safety