

# PROVIDED VS DEMANDED STOPPING SIGHT DISTANCE ADEQUACY EVALUATION

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***Summary:** In existing road design practice, despite the fact that 3D perspective is essential in order to evaluate the final outcome, the adoption of critical design parameters is restricted on a fragmented 2D road environment.*

*In current road design practice SSD adequacy is not controlled in 3D road environment. The present paper describes a SSD adequacy investigation for the most common design speed values based on the difference between the provided and the demanded SSD. The SSD DEMAND is defined based on the mass point model enriched by the actual values of grade and friction variation. On the other hand the SSD PROVIDED is described as the driver's line of sight towards the object height. Two cases were investigated; the examination of solely the road geometry ignoring the roadside environment and the case where besides the roadway alignment, the possible effect of a specific safety barrier type was encountered as well.*

*Regarding the "without safety barrier" case, the SSD investigation revealed a satisfactory SSD reserve only on compound horizontal – vertical alignments, since the negative grade area of the vertical curve revealed SSD inadequacy on tangents. For this purpose the authors suggested an increase of the Crest Vertical Curvature Rates in order adequate SSD to be provided at any point when road alignments are designed based on AASHTO guidelines.*

*The examined alignments from the "with safety barrier" point of view revealed SSD inadequacy on compound alignments despite the alignment configuration, where the suggested increase of the CVCR provided SSD safety margin only on tangents.*

## 1. INTRODUCTION

It is widely accepted that in every road environment safety is the key challenge. The misjudgment of the driving background by the driver, but mostly any abrupt alteration of the vehicle operating speed profile, especially as far as two lane rural road alignments are concerned, increase the possibility of accident involvements.

Current road design standards for example (1,2, 3,4), examine the vehicle motion from a

rather simple and fragmentary point of view, where critical geometric design parameters are being introduced without taking into account the interaction between horizontal and vertical alignment. As a result, there are cases where the road user feels uncomfortable since the length of roadway ahead that is visible to the driver; known as Sight Distance (1) is violated.

The minimum Sight Distance known as Stopping Sight Distance (SSD) is a highway geometric design element of fundamental importance. SSD constitutes the basis for the design of critical geometric elements such as vertical curvatures (crest and sag) as well as the middle ordinate values, due to roadside obstacles, on left curved divided highways and right curved sections of two lane rural roads.

As far as safety is concerned, SSD must be provided at every point along the road surface thus affecting critical road design parameters which directly impose economical considerations on both new road designs as well as road improvement projects.

In Equation 1 and Equation 2 the parameters used in determining the length of crest vertical curves in accordance with the provision of SSD are shown.

$$L = \frac{(s_2 - s_1)SSD^2}{200(\sqrt{h_1} + \sqrt{h_2})^2} \quad SSD < L(1)$$

$$L = 2SSD - \frac{200(\sqrt{h_1} + \sqrt{h_2})^2}{s_2 - s_1} \quad SSD > L \quad (2)$$

Where: L - length of vertical curve (m); SSD - stopping sight distance (m); h<sub>1</sub> - driver eye height (m) [1.08m, AASHTO 2011]; h<sub>2</sub> - object height (m) [0.60m, AASHTO 2011]; s<sub>1</sub>, s<sub>2</sub> - grade values (%).

Current design guidelines for example (1,2, 3, 4), suggest minimum values for design as well as certain grouping of horizontal and vertical alignment from which adequate SSD is provided based on experience and empirical background. The Green Book (1) for example stipulates that the vertical transition curve must be entirely designed inside the horizontal curve, where the Spanish Design Guidelines (4) specify that a vertical crest curve must be completely inside the horizontal curve including spirals.

However, horizontal and vertical arrangements of this kind are delivered as clear recommendations, since these suggestions are not an outcome of three dimensional road environment validation.

### **SSD MODEL IMPLEMENTATION**

In highway engineering, under the similar lighting conditions, the following two SSD values are reported:

- SSD<sub>DEMAND</sub> related with the ability of the vehicle to reach stop condition depending on the road, in terms of geometry.

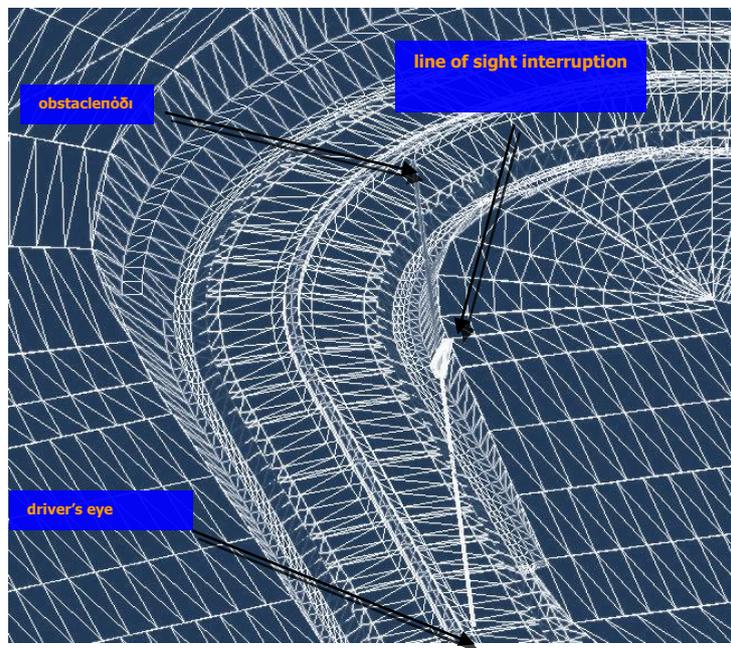
- + The driver, in terms of perception – reaction utilization;
- + The vehicle, in terms of provided dynamic characteristics.
- $SSD_{PROVIDED}$  associated with the frontal sight field visible to the driver and depends on
  - + The roadside environment (roadside obstacles);
  - + Road geometry.

According to existing design policies, for example (1, 2, 3, 4), the demanded SSD consists of two distance components: the distance traveled during driver's perception – reaction time to the instant the brakes are applied and the distance while braking to stop the vehicle. For example, the SSD model adopted by the AASHTO Design Policy is represented by Equation (3).

$$SSD = V_o t + \frac{V_o^2}{2g\left(\frac{a}{g} + s\right)} \quad (3)$$

Where:  $V_o$  (m/sec) - vehicle initial speed;  $t$  (sec) - driver's perception – reaction time [2.5sec, AASHTO, 2011];  $g$  (m/sec<sup>2</sup>) - gravitational constant;  $a$  (m/sec<sup>2</sup>) - vehicle deceleration rate [3.4m/sec<sup>2</sup>, AASHTO, 2011];  $s$  (%/100) - road grade [(+) upgrades, (-) downgrades].

The provided SSD is described as the uninterrupted line of sight between the driver's eye and the obstacle. A typical height of the driver's eye is 1.00m for passenger cars and 2.00m regarding trucks, where the obstacle height ranges between 0.50m and 1.00m. Figure 1 illustrates a line of sight interruption example on a right curved road section.



*Figure 1. Line of sight interruption on a right curved road section*

The investigation of SSD adequacy is grounded on either 2D or 3D models. The 2D SSD investigation is rather fragmentary and may underestimate or overestimate the available sight distance and consequently lead to safety violation (5). The 2D SSD investigation is based either on horizontal or vertical profile.

From the horizontal point of view, the 2D SSD adequacy is controlled by using road geometry elements referring to plan view, the vehicle speed and the horizontal offsets of both driver – obstacle from the road axis. It is clear that parameters such as road's vertical profile as well as the heights of both the driver and the obstacle are ignored. As a result, the lateral clearance area which is formed by the sequential lines of sight is theoretical.

The relevant investigation based on road's vertical profile, is conducted by utilizing the vertical road geometry. This approach is once again incomplete, since although the vehicle speed as well as the heights of both the driver and the obstacle are taken into account, the horizontal geometry is considered to be tangent, while the layout visibility is also influenced by the cross slope transition, especially at the area where the alignment's superelevation values changesign (6).

As already mentioned, in current road design practice, SSD adequacy is not controlled in 3D road environment. The past years, in order to assess the actual sight distance in real driving conditions, a number of 3D models are found in the literature (6–16) which base their performance through the correlationbetween the road surface, the ground terrain and the roadside environment. The delivered 3D models are capable to simulate accurately compound road environments where an unsuccessful arrangement of vertical and horizontal alignment as well as roadside elements may exist, and thus allow the definition of the actual vision field to the driver.

In order to investigate the SSD adequacy on 3D road environment, define the actual sight distance values,as well astake under consideration the driver's workload, a relevant research (17)recommends the usage of certain criteria in order to:

- Avoid the extremely unsafeexperience of hiding the preceding horizontal curve due to road's vertical profile
- Elude partial road disappearance areas
- Ensure the 3D perspective of a horizontal curve as to assist the driver in recognizing the formed curvature

The first of the above mentioned criteria is considered to be particularly critical from a safety point of view since the driver's ability to perceive the area where the horizontal curve begins, is a major safety prerequisite throughout the cornering process. Moreover during night driving, additional unfavorable conditions rise as the tangent direction of the headlight beams

may entirely hide the curve (18).

However most of the above research studies are focused in optimizing the available SSD by introducing either new algorithms or design parameters combinations, ignoring in many cases the roadside environment as well as certain topographic visual restraints, providing therefore an integrated, all-included SSD evaluation approach that satisfies completely designer's expectations.

The authors aim to investigate the SSD adequacy while applying the suggested geometric values according to AASHTO (1) design guidelines. Furthermore, beyond the road surface, possible impacts of elements from the roadside environment are examined well. The applied methodology is based on 3D road perspective and areas where the vision line between driver – obstacle is interrupted, thus capable to create SSD inadequacy issues, are identified.

### DEMAND AND PROVIDED SSD DETERMINATION

As already stated, in current design practice, the demanded SSD is expressed by Equation 3. The above approach ignores curved areas of horizontal and/or vertical alignment since on one hand the grade values involved in vertical curves are variable, and on the other the portion of friction provided in the longitudinal direction, is associated directly to the friction demanded laterally (19). In order to incorporate the effect of these parameters, simple considerations based on the mass point model as well as the laws of mechanics were applied.

Assuming a friction circle (19), the actual longitudinal friction demanded for braking on curved sections is expressed by Equation (4):

$$f_T = \sqrt{\left(\frac{a}{g}\right)^2 - \left(\frac{V^2}{gR} - e\right)^2} \quad (4)$$

Where:  $f_T$  - friction demand in the longitudinal direction of travel;  $V$  (m/sec) - vehicle speed;  $a$  ( $\text{m}/\text{sec}^2$ ) - vehicle deceleration rate [ $3.4\text{m}/\text{sec}^2$ , AASHTO, 2011];  $g$  ( $\text{m}/\text{sec}^2$ ) - gravitational constant;  $R$  (m) - horizontal radius;  $e$  (%/100) - road cross – slope.

Aiming to quantify the grade effect during the braking process, the laws of mechanics through Equation (5) and Equation (6) were applied, assuming time fragments of 0.01sec, in order to determine the instantaneous vehicle speed and pure braking distance respectively.

$$V_{i+1} = V_i - g(f_T + s)t \quad (5)$$

$$BD_i = V_i t - \frac{1}{2} g(f_T + s)t^2 \quad (6)$$

Where:  $V_i$  (m/sec) - vehicle speed;  $V_{i+1}$  (m/sec) - vehicle speed reduced by the deceleration

rate for  $t = 0.01\text{sec}$ ;  $t(\text{sec})$  - time fragment ( $t = 0.01\text{sec}$ );  $s (\%/100)$  - road grade in  $i$  position [(+) upgrades, (-) downgrades];  $f_T$  - friction demand in the longitudinal direction of travel;  $BD_i$  (m) - pure braking distance;  $g$  ( $\text{m}/\text{sec}^2$ ) - gravitational constant.

By applying Eq. (5) and (6) subsequently there is a sequence value  $i = k - 1$  where  $V_k$  becomes equal to zero. The corresponding value of  $\Sigma BD_{k-1}$  represents the total vehicle pure braking distance for the initial value of vehicle speed being, according to AASHTO 2011, equal to the design speed. The demanded SSD is produced by adding the final pure braking distance to the distance travelled during the driver's perception–reaction time [first component of Equation (3)] as follows:

$$SSD_{\text{demand}} = V_o t + \sum BD_{k-1} \quad (7)$$

Where:  $V_o$  ( $\text{m}/\text{sec}$ ) - vehicle initial speed;  $t$  ( $\text{sec}$ ) - driver's perception – reaction time [2.5sec (AASHTO, 2011)];  $\Sigma BD_{k-1}$  (m) total vehicle pure braking distance for the initial value of vehicle speed.

Summarizing the demanded SSD determination, the formula adopted by AASHTO, Equation (3) is applied, enriched by the utilized longitudinal friction and actual grade value portions respectively.

A prerequisite in order to calculate the available SSD is to create a digital terrain model (triangles) from the 3-D road environment. This digital terrain model can be readily provided by common road design softwares or alternatively by topographic mapping softwares, where each feature is rendered as a cluster of triangles. The available SSD is formed by driver's line of sight towards the object height at a certain offset (usually half of the driving lane) from the road centerline. Equations of analytical geometry are applied in order to describe lines of sight beginning from the driver's eye and to determine the intersection points of these lines with triangles formed by the road geometry as well as features that may restrict the driver's vision towards the object.

It is obvious that SSD adequacy is granted when:

$$SSD_{\text{DEMAND}} \leq SSD_{\text{PROVIDED}} \quad (8)$$

Where:  $SSD_{\text{DEMAND}}$  - demanded SSD;  $SSD_{\text{PROVIDED}}$  - provided SSD.

The demanded as well as the provided SSD values are defined through the difference of the road chainages between starting and ending points at an offset equal to half of the lane width.

The necessary information for defining the provided and demanded SSD as well as the procedure for the investigation of the SSD adequacy is illustrated in figure 2. The flow chart in figure 2, is incorporated in software H11 (20) applied for the assessment that follows.

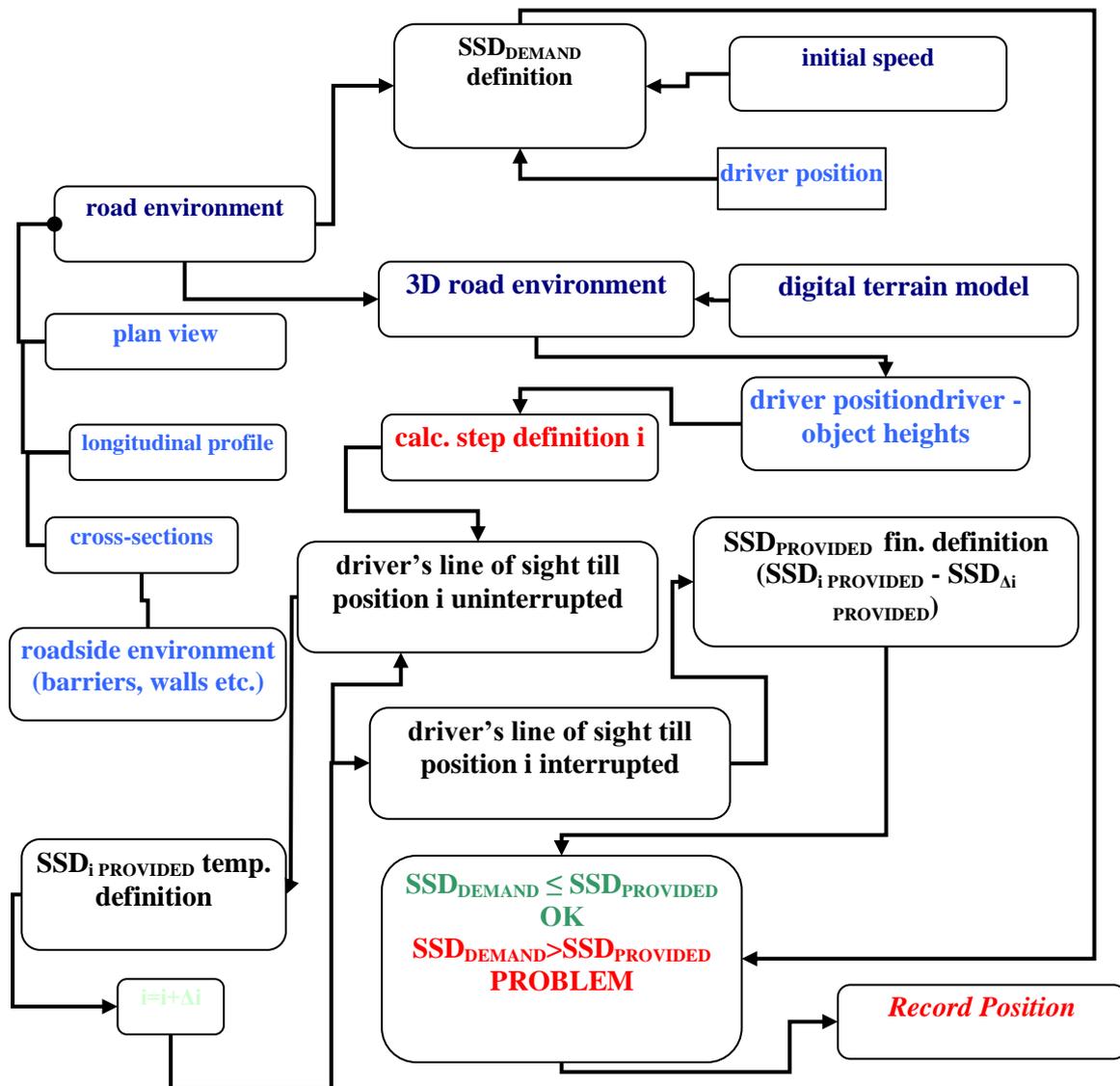


Figure 2. Flow chart of *ssd* adequacy investigation

## VALIDATION

The credibility of the H11 software was validated against an existing road section which was surveyed via laser scanner (21). The existing road section consists of an unsuccessful arrangement of vertical and horizontal alignment, where the vertical crest curve precedes, thus providing limited capability for the driver to perceive the right turning horizontal curve. The definition of the available SSD values was performed using relevant software (22).

Figure 3 illustrates the driver's frontal sight field in different locations, where the decrease of the available sight distance, as the vehicle approaches the horizontal curve, is more than evident.



**Figure 3.** 3d cross section view of a combined horizontal and vertical alignment from the driver's frontal sight field

The correlation in defining the available SSD between the above mentioned research and the present approach revealed a complete match.

### SSD ADEQUACY INVESTIGATION FOR AASHTO DESIGN GUIDELINES

In order to investigate potential safety violation for AASHTO-11 design guidelines, a wide range of combined horizontal and crest vertical alignments were examined. The compound alignments were simulated on two lane road alignments for the most common design speed values and assuming right turned curves, since a recent research study revealed this case as the most critical (6).

In the present paper the road width was assumed 2x3.75m (2x12ft approximately). Furthermore in order to evaluate possible influence from the roadside environment, the case of embankments with a w-beam safety barrier (0.685m high) was examined as well, offset 1.50m from the pavement edge line (23).

The pavement cross slopes were assumed 6% on curves and 2% on tangents, where the gradient verge was taken 8%.

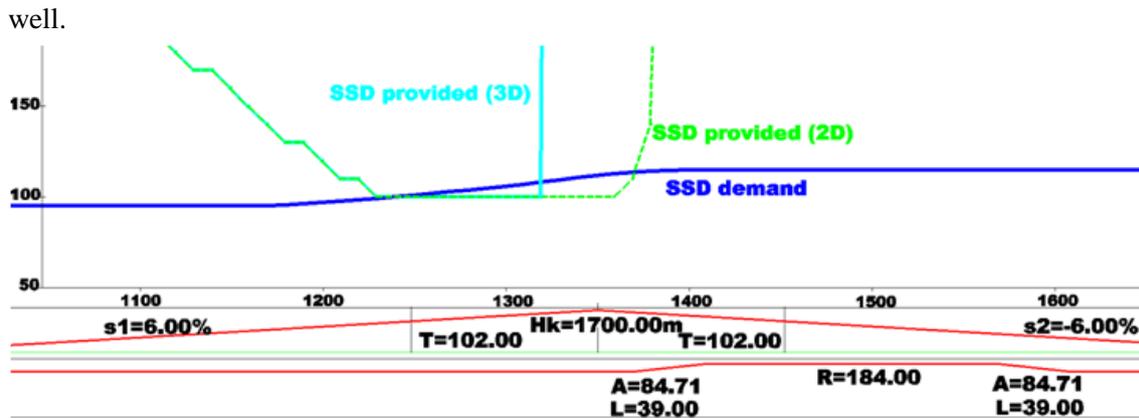
Table 1 illustrates, the minimum values of crucial design parameters accruing from the selected design speed values and used in the SSD adequacy investigation that follows.

**Table 1.** Crucial design values used in the ssd adequacy investigation

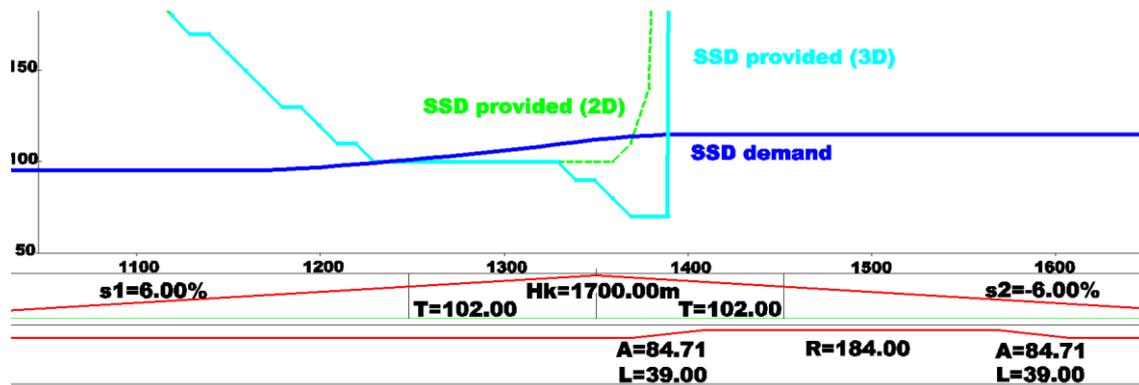
$V_{design}$ (km/h)	$R_{min}$ (m)	$L_{desirable}$ (m)	$K_{min}$ (m)	$S_{range}$ (%)
50	79	28	7	-7 - +7
60	123	33	11	-6 - +6
70	184	39	17	-6 - +6
80	252	44	26	-5 - +5
90	336	50	39	-5 - +5

Note  $V_{design}$ : design speed,  $R_{min}$ : minimum horizontal radius,  $L_{desirable}$ : desirable length of spiral curve,  $K_{min}$ : rate of crest vertical curve,  $s_{range}$ : grade range

Figure 4 shows an example regarding SSD adequacy examination on a 3D road surface (without the presence of safety barriers) for 70km/h design speed, where three different types of SSD are shown. The abscissa axis represents the road chainage where the horizontal and vertical curvatures are shown linearly. Figure 5 illustrates exactly the same 3D compound alignment as well as design speed (70km/h) where the roadway environment (safety barriers) is included as



**Figure 4.** Ssd adequacy investigation for 70km/h design speed without the presence of safety barriers  
*Note*  $SSD_{provided} (2D)$ : SSD Adequacy Investigation Based on Roadway's Longitudinal Profile.  
 $SSD_{provided} (2D)$  and  $SSD_{provided} (3D)$  overlay up to chainage 1320 approximately.  
 Vertical Vertex chainage: 1350



**Figure 5.** Ssd adequacy investigation for 70km/h design speed with the presence of safety barriers  
*Note*  $SSD_{provided} (2D)$ : SSD Adequacy Investigation Based on Roadway's Longitudinal Profile.  
 $SSD_{provided} (2D)$  and  $SSD_{provided} (3D)$  overlay up to chainage 1330 approximately.  
 Vertical Vertex chainage: 1350

In both figures, since both the alignment and the design speed remain constant, it is clear that the  $SSD_{PROVIDED} (2D)$  as well as the  $SSD_{DEMAND}$  values are unaffected. A closer look between these two approaches reveals the same underdesign zone, located at the area where the black line ( $SSD_{DEMAND}$ ) overlaps the dashed one [ $SSD_{PROVIDED} (2D)$ ]. This finding is not surprising since, according to AASHTO (1), the formula applied for the vertical curve definition (Equation 1), which is independent to the horizontal alignment, adopts SSD values extracted for 0% grade and not the unfavorable case of negative grade values.

In figure 4, where the case without the safety barrier is shown, it can be seen that actual SSD inadequacy (3D) is less than the relevant in 2D assessment.

The contrary findings can be seen in figure 5, case with roadway environment included, where the SSD adequacy is further more violated. In other words the presence of safety barriers has a negative effect in the SSD safety margin.

As mentioned above, the AASHTO (1) Design Guidelines adopt minimum Crest Vertical Curve Rates (CVCR) based on 0% SSD values, which produce SSD inadequacy at the negative grade area of the vertical curve. In order to ensure SSD sufficiency for the entire vertical curve, the authors suggest a slight increase of the vertical curvature rate (Figure 6) in accordance with the design speed. The suggested CVCR are rounded values, still based on Equation 1 where the most unfavorable grade rates from Table 1 are utilized.

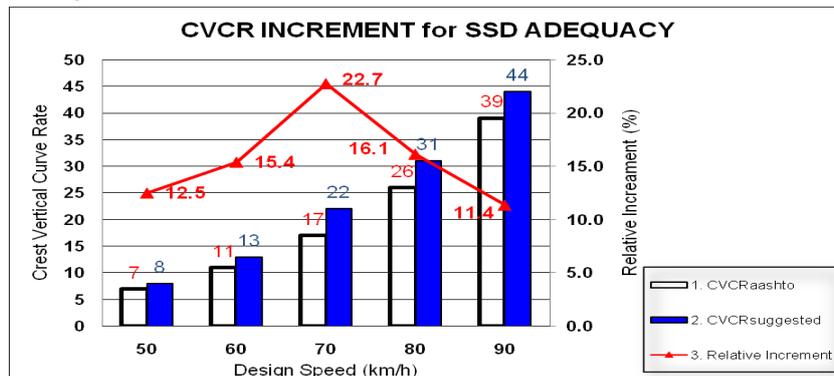


Figure 6. Cvr increment for ssd adequacy

Where: 1; 2; 3.

In order the SSD adequacy investigation for roadway as well as combined roadway and roadside environment, as assessed in the present paper, to be more comprehensive and directorial, figure 7 – figure 11 display the length of SSD reserve where in the horizontal axis the “sliding” of the vertical vertex across the horizontal alignment is shown every 50m and the vertical axis illustrates the length of the roadway partially disappeared from the driver’s view.

For example in Figure 7, when the vertical vertex (formed by  $s_1 = -7\%$ ,  $s_2 = 7\%$  and  $CVCR = 7$ , which refer to 50km/h design speed) is placed on Chainage 1550, where in plan view this point is the beginning of a tangent, in the “Without Safety Barrier” case, the partial road disappearance is 32m approximately.

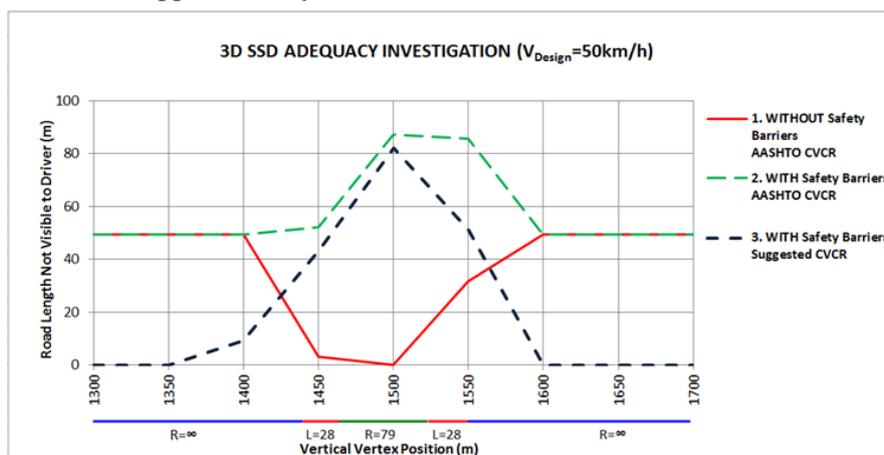
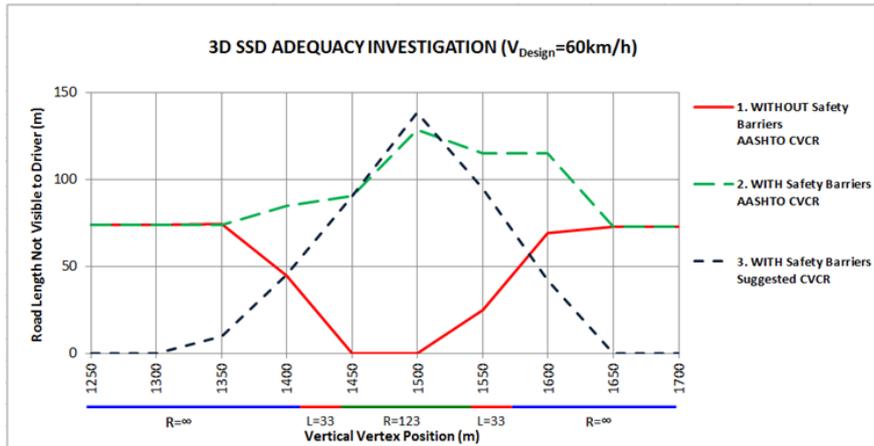


Figure 7. Ssd adequacy investigation chart for  $v_{design} = 50\text{km/h}$

Note calculation Step = 50m.

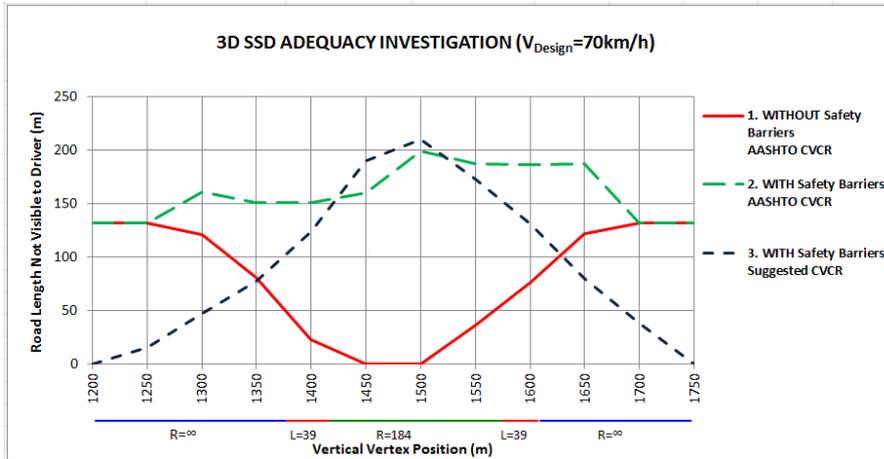
Where: 1; 2; 3.



**Figure 8.** Ssd adequacy investigation chart for  $v_{design}=60km/h$

Note calculation Step = 50m.

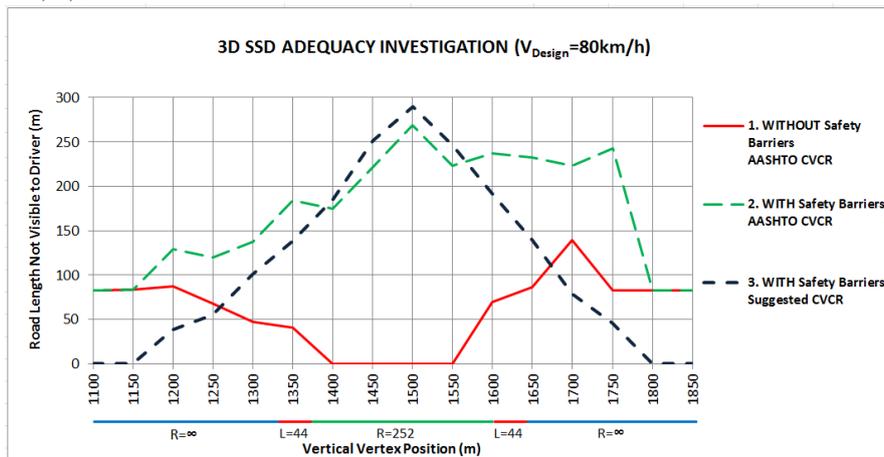
Where: 1; 2; 3.



**Figure 9.** Ssd adequacy investigation chart for  $v_{design}=70km/h$

Note calculation Step = 50m.

Where: 1; 2; 3.



**Figure 10.** Ssd adequacy investigation chart for  $v_{design}=80km/h$

Note calculation Step = 50m.

Where: 1; 2; 3.

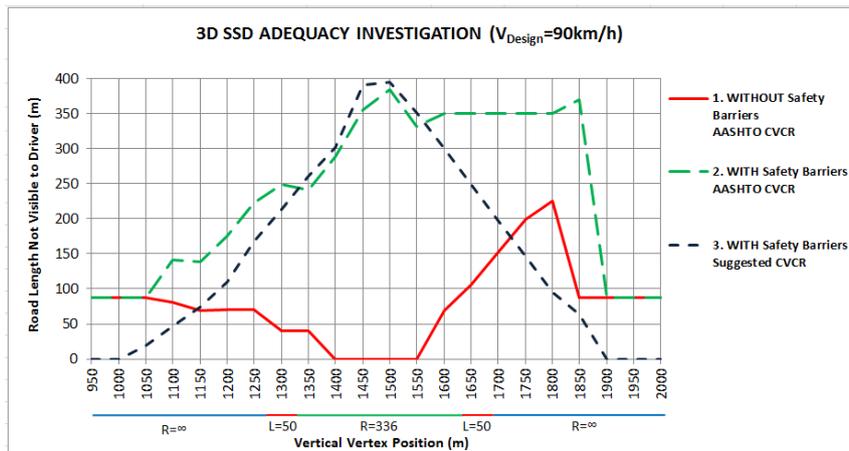


Figure 11. Ssd adequacy investigation chart for  $v_{design}=90\text{km/h}$

Note calculation Step = 50m.

Where: 1; 2; 3.

The general remark from the overview of figure 7 – figure 11 is that the presence of safety barriers has a dissimilar effect in SSD adequacy compared to the investigation of the road geometry itself. Moreover, areas with abrupt label alternations referring to the same data series, are due to the existence of more than one overlapping zones between  $SSD_{provided}$  and  $SSD_{demand}$  values. In such cases, where the overlapping zone exceeded 30m and the between adequate SSD zone was less than 100m, the authors considered the unified area as SSD inadequate. An example, shown in figure 12, is drawn for the most critical illustration of figure 11, regarding the “without safety barrier” case for  $V_{Design} = 90\text{km/h}$  and the vertical vertex positioned at chainage 1800, where the SSD inadequacy was considered 225.5m.

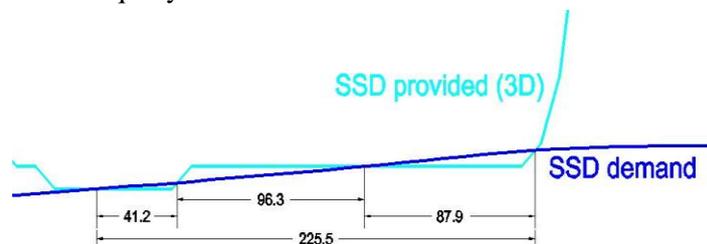


Figure 12. Detail of ssd adequacy investigation

Note  $V_{Design} = 90\text{km/h}$ , without safety barrier case, chainage of vertical vertex 1800.

Commenting further on the isolated road geometry case, it can be seen that the SSD adequacy improves as the vertical vertex is located near the area of the horizontal curve confirming recent research study (6) according to which *the location of the vertical midpoint that maximizes available sight distance is located before the horizontal vertex.*

On the other hand, the presence of safety barriers does not provide adequate SSD on compound alignments, despite the horizontal and vertical alignment arrangement. The increment of the CVCR, as showed in figure 6, warrants SSD adequacy for any horizontal – vertical alignment arrangement for the “without safety barrier” case, and grants sufficient SSD reserve for the “with safety barrier” case only on tangents.

## CONCLUSIONS

In this paper a SSD adequacy investigation is carried out for a wide range of design speed values based on the difference between the provided and the demanded SSD. The  $SSD_{DEMAND}$  is defined based on the mass point model enriched by the actual values of grade and friction variation due to vertical curves and vehicle cornering respectively. On the other hand the  $SSD_{PROVIDED}$  is described as the driver's line of sight towards the object height at a certain offset. The SSD adequacy investigation consists of two cases; the case where only the road geometry was examined ignoring the roadside environment and the case where besides the roadway alignment, the possible effect of a specific safety barrier type (w-beam), was encountered as well.

Regarding the "without safety barrier" case, the SSD investigation revealed a satisfactory SSD reserve only in areas of compound horizontal – vertical alignments, since the negative grade area of the vertical curve revealed SSD inadequacy on tangents. The authors suggested an increase of the CVCR in order adequate SSDs to be provided at any point when road alignments are designed based on AASHTO guidelines.

The examined alignments from the "with safety barrier" point of view revealed SSD inadequacy on compound alignments despite the alignment configuration, where the suggested increase of the CVCR provided SSD safety margin only on tangents.

The SSD adequacy investigation approach as described in the present paper can be applied to any alignment including any kind or combination of roadside formations where for example in retaining wall areas the sight distance is furthermore restricted.

The present paper points out critical SSD situations based on the minimum geometric design parameter values. Further qualitative research is required in order to evaluate the influence of every parameter independently. It is evident that this kind of practice involves many constraints, rising from the road side environment and the topography, given that the present procedure can be applied on existing road sections, left turns of divided highways as well as safety investigation onpassing maneuvers.

It is also necessary to underline the fact that the parameters used in the present paper (speed values, perception reaction time etc.) refer to daylight driving conditions, as the vehicle speed values in night time driving conditions are 6km/h – 15km/h less.

Finally, it should not be ignored the fact that the human factor, in addition to perception – reaction procedure as well as the friction reserve utilized in the lateral direction during the braking process, might impose additional restrictions and consequently influence the braking process to some extent.

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