# Design Considerations of Compound Alignments Resulting from Visibility Restrictions by Median Jersey Barriers

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**Abstract**

The paper investigates SSD adequacy on the passing lane of high-speed divided alignments for the most critical case where left-turned horizontal curves are overlaid with crest vertical curvature rates. The process addresses potential SSD shortage zones under the German RAA, 2008 road design guidelines for the highest speed value (130km/h) by examining 24 cases consisting of 6 horizontal alignments, each one combined with 4 different vertical alignments. The analysis, through the definition of the length and the maximum vertical distance of the driver's sightline blocked by the median barrier, along with revised values of object heights, revealed extensive areas with SSD inadequacy. Aiming to preserve design consistency as well as driver expectations, the authors quantified the safety impact in such areas based on parameters associated to SSD. Moreover, taking under consideration improved braking performance of modern vehicles, realistic and therefore acceptable arrangements of such compound alignments are delivered for practitioners.

***Keywords:*** *Stopping sight distance, speed, median barrier, compound alignment.*

## *1. Introduction and Research Objective*

In current highway design practice (e.g. 1-4), the three-dimensional highway geometry is still addressed by designing it in two independent and mostly uncorrelated two phase two-dimensional stages, namely, the horizontal alignment and the vertical profile. This 2-D approach while inevitable in many cases has proven to be associated with design misconceptions that influence the design performance adversely. Such a typical case of design misconception is the determination of the critical parameter of Stopping Sight Distance (SSD).

The 2-D SSD calculation is inexact, fragmentary and may produce design deficiencies due to inaccurate calculation of the available sight distance. Hassan et al. (5), for example, stated that 2-D SSD investigation might underestimate or overestimate the available sight distance and consequently lead to design criteria violation. Furthermore, a pure 2-D SSD design control can be detrimental to the cost or performance of a divided highway. This is because for cases with SSD inadequacies a usual solution is either to increase the inner shoulder width or decrease the posted speed under wet pavement conditions, the latter being a common case in Europe due to a lack of available land. Therefore contemporary highway design policies try to define 3-D design rules that assist designers efficiently and address the SSD inadequacy issue. For example, the Green Book (1) as well as RAA, 2008 (2) design guidelines stress that, in order to achieve SSD provision a basic prerequisite is the vertical curve to be entirely designed inside the horizontal curve. In the relevant Spanish design guidelines (4) the desired horizontal – vertical curve arrangement is reached when the vertical crest curve falls completely inside the horizontal curve including spirals. However, such provisions do not actually address all design cases and therefore a final 3-D perspective evaluation of the roadway is inevitable (2).

In recognition of the deficiencies of 2-D design approach in SSD evaluation, many researchers have started addressing the problem directly in three dimensions. One of the first researchers that assessed the available sight distance on 3-D alignment, Sanchez (6), studied the interaction between the sight distance and the 3-D combined alignment idealized into a net of triangles using Inroads software. Although this methodology was accurate, it was very time consuming since the available sight distance was determined graphically (not analytically).

Several years later, Hassan et al. (7) presented an analytical model for computing available sight distance on combined horizontal and vertical highway alignments, using parametric finite elements (4, 6 and 8-node rectangular elements as well as 3-node triangular elements) to represent the highway and sight obstructions. The proposed model examined the driver's sight line, which was represented by a straight line between the driver's eye and an object, against all the possible sight obstructions, by using an iterative procedure.

Lovell et al. (8) developed a method to calculate the sight distance based on horizontal geometry, without considering the effect of vertical geometry. Nehate and Rys (9), described a methodology to define the available sight distance using Global Positioning System (GPS) data by examining the intersection of line of sight with the elements representing the road surface. However, the available sight distance was not based on the road's compound (horizontal and vertical) alignment.

In the past years, in order to evaluate the actual sight distance in real driving conditions, a number of 3-D models are found in the literature (10-16) aiming to optimize the available sight distance.
Recently, Kim and Lovell (17) delivered a 3-D sight distance evaluation method where an algorithm is used to determine the maximum available sight distance using computational geometry and thin plate spline interpolation to represent the surface of the road. The available sight distance is measured by finding the shortest line that does not intersect any obstacle.

Jha et al. (18) proposed a similar to the present paper 3-D methodology for measuring sight distance, utilizing triangulation methods via an introduced for this purpose algorithm, consisting of three stages, namely road surface development, virtual field of view surface development, and virtual line of sight plane development. However, the process involved multiple software platforms, thus delivering an accurate but non-flexible outcome.

The above mentioned 3-D models are capable of simulating accurately compound road environments where an undesirable arrangement of vertical and horizontal alignment may exist, and thus allow the definition of the actual vision field to the driver. However, as already stated above, most of the previously mentioned research studies are focused in optimizing the available SSD by introducing either new algorithms or design parameter combinations, ignoring in many cases the topographic visual restraints. Moreover, none of the above mentioned approaches suggested a comprehensive methodology to simulate from a 3-D perspective concurrently both the alignment design and the vehicle dynamics on the road surface during emergency braking.

Under this scope, the paper aims to point out shortcomings in terms of SSD adequacy for cases where horizontal and vertical parameters of compound alignments are selected based on values inferred by the design speed, without assessing in advance their interaction.

## *2. SSD Modeling Proposal*

The SSD adequacy investigation that follows is an accurate procedure, based on a realistic representation of the roadway features as well as the vehicle dynamics. As a result, the ground, travel surfaces and roadside elements, along with actual friction and grade values during emergency braking conditions, are all taken into account. The process is based on the difference between the available and the demanded SSD, where SSD adequacy is granted when:

$$SSD_{DEMANDED} \leq SSD_{AVAILABLE} \qquad (1)$$

On one hand, $SSD_{DEMANDED}$ is defined based on the point mass model introduced by many design guidelines worldwide, enriched by the actual values of grade and friction variation due to the effect of vertical curves and vehicle cornering respectively.

$SSD_{AVAILABLE}$ on the other is termed as the driver's line of sight towards the object height, both at a certain offset in 3D roadway environment.

The developed procedure, analytically outlined through (19) and (20), among others identifies areas of interrupted vision lines between driver and obstacle at left-turn curves due to the presence of median concrete barriers, where the vision line lengths are less than the required distance necessary to bring the vehicle safely to a stop. It is evident that high speed affects negatively such areas of SSD inadequacy (road length not visible to the driver). A brief description of the methodology is provided in the following paragraphs.

According to existing design policies the demanded SSD consists of two distance components: the distance travelled 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 RAA 2008 design policy is represented by Equation (2).

$$SSD = V_o t + \frac{V_o^2}{2g(\frac{a}{g} + s)} \qquad (2)$$

where :
Vo (m/sec) : vehicle initial speed (usually the design speed)
t (sec) : driver's perception – reaction time [2.0sec (RAA, 2008)]
g (m/sec2) : gravitational constant
a (m/sec2) : vehicle deceleration rate [3.7m/sec2 (RAA, 2008)]

s (%/100) : road grade [(+) upgrades, (-) downgrades]

However the above approach ignores curved areas of both horizontal and vertical alignment, since, on one hand, the portion of friction provided in the longitudinal direction, assigned to serve the braking process, is associated directly to the friction demanded laterally, and on the other, the grade values involved in vertical curves are variable. 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 respectively.

Assuming a friction circle, the actual longitudinal friction provided for braking on curved sections is expressed by Equation (3):

$$f_T = \sqrt{\left(\frac{a}{g}\right)^2 - \left(\frac{V^2}{gR} - e\right)^2} \qquad (3)$$

where :
fT : friction demand in the longitudinal direction of travel
V (m/sec) : vehicle speed
a (m/sec2) : vehicle deceleration rate [3.7m/sec2 (RAA, 2008)]
g (m/sec2) : 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 (4) and Equation (5) were applied, assuming time fragments (steps) of 0.01sec, in order to determine both the instantaneous vehicle speed and pure braking distance.

$$V_{i+1} = V_i - g(f_T + s)t \qquad (4)$$

$$BD_i = V_i t - \frac{1}{2} g(f_T + s)t^2 \qquad (5)$$

where :
Vi (m/sec) : vehicle speed at a specific station i
Vi+1 (m/sec) : vehicle speed reduced by the deceleration rate for t = 0.01sec
t  (sec) : time fragment (t = 0.01sec)
s (%/100) : road grade in i position [(+) upgrades, (-) downgrades]
fT : friction demand in the longitudinal direction of travel
BDi (m) : pure braking distance
g (m/sec2) : gravitational constant

By applying Eq. (4) and (5) subsequently there is a sequence value i=k-1 where Vk becomes equal to zero. The corresponding value of ΣBDk-1 represents the total vehicle pure braking distance for the initial value of vehicle speed being, according to RAA 2008, 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 (2)] as follows:

$$SSD_{demand} = V_o t + \sum BD_{k-1} \quad (6)$$

where :
Vo (m/sec) : vehicle initial speed
t (sec) : driver's perception – reaction time [2.5sec (RAA, 2008)]
ΣBDk-1 (m) total vehicle pure braking distance for the initial value of vehicle speed

Summarizing the demanded SSD determination, the formula adopted by RAA, Equation (2) is applied, enriched by the utilized longitudinal friction and actual grade value portions respectively.

The available SSD is described as the uninterrupted line of sight between the driver's eye and the obstacle, both at certain heights and offset (usually the middle of the examined lane) from the road centerline. 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 software or alternatively by topographic mapping software, where each feature is rendered as a cluster of triangles. Equations of analytical geometry are utilized in order to describe the above-mentioned line of sight and determine its intersection points with planes formed by the road geometry or features that restrict the driver's vision towards the object.

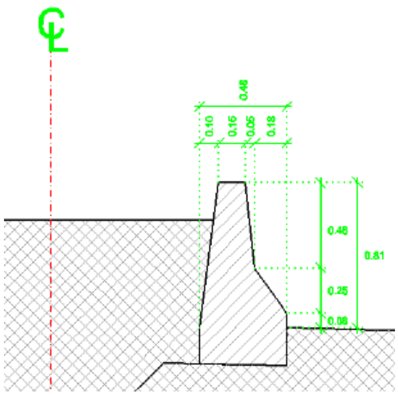
The precision of the available SSD definition depends on the selected incremental distance (calculation iteration) between two sequential available SSDs. In the present analysis, the calculation iteration was set equal to 10m, in order to reduce the calculation time for each run. Through the proposed approach, the objective of the paper is initially to assess SSD adequacy on the passing lane of high speed (V=130km/h) left curved divided highways overlaid with crest vertical curvature. Moreover, the research aims to quantify their safety impact based on parameters associated to SSD, where taking under consideration improved braking performance of modern vehicles, deliver realistic and therefore acceptable arrangements of such compound alignments.

## *3. Median Barrier Design on Divided Highways*

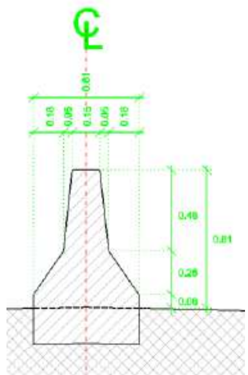
Roadside barriers are placed in the longitudinal direction of high-speed roadways to redirect errant vehicles and shield them from hitting obstacles along either side of the road (1, 21). Barriers may also be placed in the median area to prevent out-of-control vehicles in one direction from crossing to the other road direction, in which case they are called median barriers. The presence of median barriers on left-turn curved divided highways, although increase the level of safety, under certain circumstances may affect the sight distance available to drivers (22).

The selection process of the appropriate traffic barrier type is a complicated task since many parameters are involved, where the most important goals to be served are safety, operational and economic considerations. As for providing SSD adequacy, the barrier height but especially the clearance between the barrier and the left edge of the passing lane, known as inner shoulder width, seems to be the most critical issues (e.g. 1, 23).

Since on divided highways, in cases of potential vehicle collisions, rather shallow impact angles are expected, at least in the median areas, as well as for maintenance reasons, rigid concrete barrier types seem to be more appropriate (21). However, in any utilized median barrier type, vehicles travelling on the opposite direction should not interrupt the driver's line of sight. Figure 1(a,b) shows a cross-section example of "New Jersey" concrete barrier type with 0.81m height, as shown in Roadside Design Guide (21) as well as utilized in highways designed in Greece.



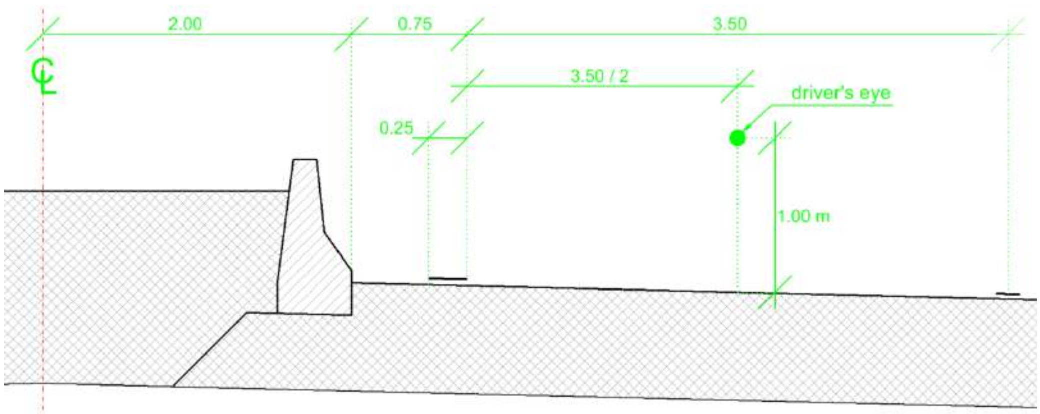

(a)



(b)

*(a,b) Example Dimensions of "New Jersey" Concrete Median Barrier Type.*

*(c)*




*Semi Cross Section View at the Inner Shoulder Area.*

***Figure 1 (a,b,c).*** *Example Dimensions of "New Jersey" Concrete Median Barrier Type (a,b) and Semi Cross Section View at the Inner Shoulder Area (c).*

## *4. Existing Sight Distance Approach on Left Curved Divided Highways*

Although the necessity for SSD adequacy on left-turned curves of divided highways is emphasized in current design practice (e.g. 1-4, 24), no explicit process is provided to accurately implement this control. The only available tool in defining the available SSD is the

2D approach according to which $SSD_{AVAILABLE}$ is defined by the lateral clearance and the curve radius. However, this consideration applies only to circular curves longer than the sight distance where both driver and obstacle are positioned on the circular curve (1). Moreover, between the driver height and the obstacle height, there is no assurance whether the barrier height and/or the presence of a vertical curve does not obstruct the driver's line of sight.

The breakpoint of SSD adequacy in current practice is defined by equalizing $SSD_{AVAILABLE}$ and $SSD_{DEMANDED}$ (Equation 1) where two different options exist:

- the determination of the examined curve's inferred safe speed referring to the given geometry (horizontal, vertical, typical cross-section) which may reflect the area's posted speed value;
- the definition of the inner shoulder width for a desired speed value on the curved road geometry

Based on this concept, many researchers addressed their concerns in SSD provision for left-turn curved divided highways. For example Arndt (25) mentioned that the SSD adequacy process using the design criteria listed in the current design guidelines would lead to very wide shoulders, which was described as uneconomical, where in case of maintaining the original shoulder widths, rather conservative speed limit values should be implemented (26). However, the adoption of the conventional approach, provided by current practice, besides cost or performance impacts, may lead to road safety violation as well. This is because either vehicles (especially motorcyclists) potentially can use the widened inner shoulder as an extra traffic lane for passing manoeuvres, or areas with unexpected speed discontinuity will emerge.
Klam et. al. (27), aiming to improve available SSD in intersection areas, suggested the arrangement of shorter barriers (0.508m high), referred to as low-profile barriers, in different locations in Texas and Florida, where merely the Test Level 2 criteria (70km/h) of the NCHRP Report 350 (28) were reached. As to increase the Test Level a stabilized rail was suggested to be attached to the low-profile barrier.

In another research (29), the risk evaluation of inadequate available SSD due to the presence of median barriers was examined via reliability analysis. A methodology was presented to calculate the probability of non-compliance that describes the associated risk of a driver requiring a sight distance greater than available in order to make a safe stop. However, since the simple 2D approach was utilized for available sight distance, the accuracy of the results is uncertain.

Sarhan et. al. (22) using a previously developed software, examined the impact of roadside and median barriers on the available SSD on horizontal curves when overlapped with various vertical alignments. The results confirmed previous findings according to which the available sight distance depends on the type of the vertical alignment and the curvature of crest or sag vertical curves overlapping on the horizontal curve. The authors delivered charts, as an easy-to-use tool by designers, to estimate the available stopping sight distance on horizontal curves overlapped with a specific vertical alignment.

In AASHTO design guidelines, as far as divided highways are concerned, the recommended distance between the edge of the travelled way and the median barrier could deliver available SSD values less than the relevant demanded in order to safely lead a vehicle to a complete stop condition, before striking a sudden object (22).

Although the conventional SSD approach is adopted in the German RAA 2008 design guidelines as well, in situations of SSD shortage, it is recommended to modify the road alignment or decrease the speed limit. However, in every case SSD adequacy is advised to be assessed in 3D roadway environment, where no further instructions are provided (2).

Since the conventional approach practically fails to address SSD adequacy, in certain cases (24), less-conservative criteria for the parameters involved in the SSD adequacy process are introduced which are believed to be more realistic (ex. increased values of deceleration rate and obstacle height).

As the design policies worldwide associate vehicle speed with the definition of critical vertical design parameters via SSD provision, based in 2D approach, the existence of a reliable tool to effectively and accurately perform SSD adequacy investigation on compound alignments for a given speed value seems essential.

Moreover, aiming to provide a clear outlook of the interaction as well as appropriate arrangement between the horizontal and vertical alignment, none of the relevant research studies examined the impact of median barriers in SSD adequacy concurrently from the 3D alignment design viewpoint along with the vehicle dynamics.

## *5. SSD Adequacy Investigation on Compound Divided Highways*

The assessment was investigated on high speed left curved divided highway segments overlapped with crest vertical curvature under the German RAA, 2008 design guidelines (2), assuming various synthetic alignments. More specifically, the potential safety violation was performed for 130km/h, where the control horizontal and crest vertical radii are R=900m and Hk=13000m respectively. This crest vertical radii is equivalent to a crest vertical rate of K=130m under the AASHTO, 2018 design guidelines. The crest vertical curve's boundary grade values were set to the maximum values of 4% and -4% (symmetrical). It is clear that the speed value of 130km/h refers to the roadway's posted speed, of which the road surface condition is assumed wet.

The examined cross section at the barrier area is shown in Figure 1(c) and consists of a passing lane and an inner shoulder of 3.50m and 0.75m respectively, where the lateral offsets of both driver and object from the edge of the passing lane were assumed half of the lane width (1.75m). The height of the median barrier was set to 0.90m (0.81m plus safety margin), where its curvature at the top increases the inner shoulder by 0.23m (Figure 1a).
As far as parameters related to SSD are concerned, the RAA, 2008 design guidelines adopt deceleration rate and the driver's perception – reaction time values of 3.7m/sec2 and 2.0sec respectively. The heights for both the driver's eye and object were set to 1.00m.

Commenting further on the object height, it must be stressed that the German RAA 2008 design guidelines, in order to increase safety during night driving, determine the crest vertical curvature rate based on utilizing the vehicle's tail lights as object height (0.50m). However, in cases of SSD investigation where for example median barriers are present, in order the driver to be able to identify a slow moving or stopped vehicle due to traffic collision, the object height is assumed equivalent to the driver's eye height (1.00m).

As already stated, the sight line in median barriers should not be allowed in any case to go beyond the edge of travelled way on the opposite direction so that the available SSD would not depend on whether there is a vehicle in the opposite direction. Therefore, in order for all the examined cases of compound alignments to be treated equally, the following simple calculations took place.

Initially, assuming that the median width (MW) retains the RAA, 2008 control value of 2m per direction of travel [Figure 1(c), (MW=2x2m)], the minimum (centerline) horizontal radius was determined for which the driver's sight line is tangential to the inner edge of the opposite passing lane. The calculation revealed R=1200m approximately. Therefore, in order the horizontal alignment to be designed in accordance with the control value of R=900m, the authors calculated the required median width (MW), which was found to be MW=2x3.2m approximately. Both values were defined for the most unfavorable SSD case according to which the vehicle immobilises at the ending area of the vertical transition (s=-4%).

As a result when utilizing the control value of R=900m, the median width was assumed 2x3.2m, where for R>1200m, a median width of 2x2m was utilized as shown in Figure 1(c).
SSD adequacy evaluation was carried out by utilizing the following stages:

- alignment selection
- definition of calculation step along the alignment where the vehicle's braking performance is examined (100m in the present analysis)
- calculation of $SSD_{DEMANDED}$
- $SSD_{AVAILABLE}$ forced equal to $SSD_{DEMANDED}$
- definition of intersection points between the driver to object sightline and the median barriers area in 3D
- recording of these points in order to calculate, for the most unfavorable case the following values
    - vertical difference of the sightline from the barriers' top
    - amended object height in order the driver's sightline to be non-obstructed due to the median barriers

The above values at the median barrier area, which are determined in 3D perspective, are shown through a sketch in Figure 2(a).

In order have a more clear view on the impact of median jersey barriers in the design of compound alignments, the assessment included 24 cases consisting of 6 horizontal alignments where each one is combined with 4 different vertical alignments. In particular, horizontal radii values of R=900m, R=1500m, R=2000m, R=2500m, R=3000m and R=3500m, were combined with crest vertical curve rates of Hk=13000, Hk=20000, Hk=25000 and Hk=40000m.

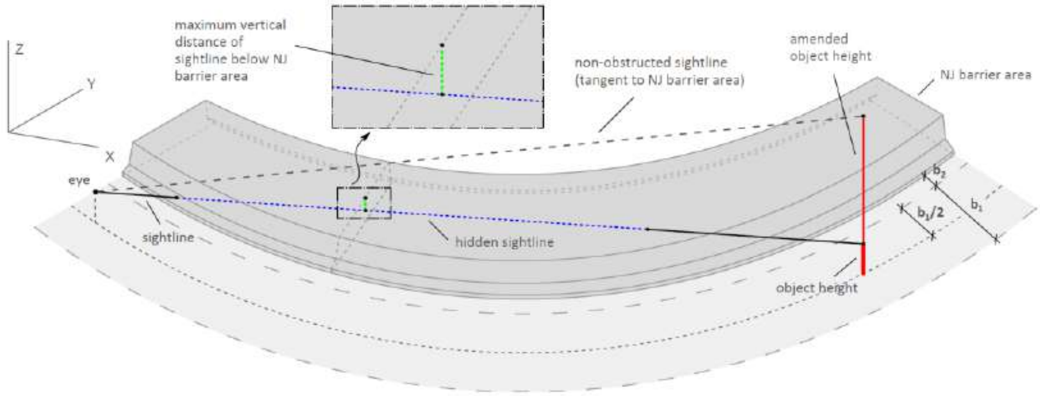
The impact of broader design values seems not necessary to be examined for the reasons outlined below. From the horizontal design point of view, by basic calculations and utilizing once again the most unfavorable SSD value, for which the vehicle stops just before the exit grade (s=-4%) of the vertical transition, the radius value for which the line of sight strikes tangentially the inner barrier face is slightly over 3500m. From the relevant vertical design point of view, a further rise of the crest vertical curvature rates will generate extended areas with low drainage capability where besides the safety concerns, will result in increasing the construction and maintenance costs of the required drainage layouts as well.

The process initially was performed for the control horizontal, crest vertical curvature rate and grade values of RAA (2008) guidelines for 130km/h (R=900m, Hk=13000m, s=±4.0% respectively). The utilised superelevation values were also in accordance with RAA, ranging between e=6.0% for R=900m to e=2.5% for R=3000m.

The assessment includes the examination of the braking process of the vehicle throughout the variable grade area (prior, during and after), thus incorporating the areas with constant grades as well.

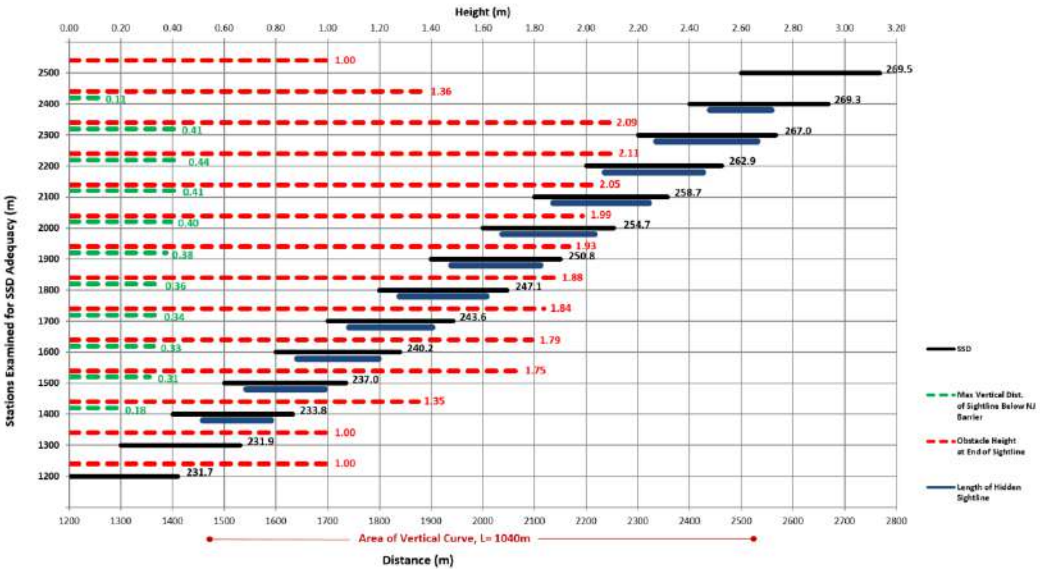
An example of the process for R=1500m and Hk=13000m is shown in Figure 2(b). More specifically, Figure 2(b) shows certain sets (14 sets) of horizontal bars (4 bars per examined station) where SSD adequacy is examined at fixed distances every 100m. The primary (bottom) horizontal axis shows the linear projection of the horizontal circular arc where the vertical transition area (St.1480 – St.2520) is illustrated as well. The vertical axis represents the same fixed locations (every 100m) of the examined alignment where the vehicle's SSD process is initiated. The bars in black color show SSD values referring to the relevant station, where the lines in blue express the length of the driver's sightline blocked by the median width in 3-D perspective. Both black and blue bars are expressed along the horizontal alignment's centerline. For example at St.2000, which is located inside the vertical curve, the SSD is 254.7m, where the sight line is blocked for 178m (St.2038 – St.2216). The secondary (top) horizontal axis of Figure 2(b) quantifies the max vertical distance of the sightline below the New Jersey barrier (dashed green line) as well as the modified object height (dashed red line) in order the sightline to pass tangentially over the most unfavorable point of the barrier. For the same Station (St.2000), it can be seen that the most unfavorable driver's sightline position (located somewhere inside the relevant blue line) is 0.40m below the top of the NJ barrier, where in order to retrieve SSD adequacy, the object height should be set to 1.99m.

From Figure 2(b) it can be seen that throughout the area where the horizontal curve is superimposed with the vertical curve, the sightline of the driver towards the object is continuously blocked [length of hidden sightline (blue line) is overlapped, object height (red line) is above 1.00m].




*Note. Inner shoulder width: 0.75m, lane width: 3.50m, Barrier height: 0.90m (0.81m + safety margin).*

*(a) Obstructed driver's sightline*




*Note. i. Secondary horizontal axis (Height) quantifies max vertical distance of the sightline below the New Jersey barrier (dashed green line) and modified object height (dashed red line)*

*ii. Horizontal alignment (R=1500m) which encloses a vertical transition area (Hk=13000m, L=1040m) between grades of ±4%.*

*(b) Outcomes of the SSD adequacy investigation*

***Figure 2(a,b).** Obstructed driver's sightline (a) and Outcomes of the SSD adequacy investigation (b).*

From Figure 2(a), it is evident that the value of maximum vertical distance of the sightline below the New Jersey barrier (dashed green line) is at a certain point along the driver's line of sight. This value does not determine directly the value of the amended object height (dashed red line). Therefore,if the barrier height for some reason is further raised, the max vertical distance of the sightline below the New Jersey barrier (dashed green line) will be raised accordingly, however not the same finding will be noticed for the new object height (red line) which increases as a function of the distance from the driver's eye. The SSD evaluation was drawn assuming 0.90m as barrier height [0.81m+safety margin (plantation, construction

tolerance etc.)]. As a result, assuming as barrier height the original value of 0.81m, SSD adequacy would be granted only in the very beginning and ending areas of the vertical transition.
The analysis of the total examined alignments revealed that by increasing the horizontal radius, inside the vertical transition area, the conflict area in terms of both object height amendment necessity as well as length of blocked driver's sightline, increases up to a certain point as well. However, as the radii values increase further, the lengths of the blocked sightlines decrease in advance of the object height amendment requirement.

The most critical SSD inadequacy area is found in the negative grade area and close to the end of the vertical transition (see St.2200 in Figure 2(b) where the object height should be raised up to 2.11m in order to be visible).

A general finding is that RAA, 2008 design guidelines fail to warrant safety during emergency braking of a vehicle moving with 130km/h on the passing lane of such compound alignments, since the median barrier obstructs the line sight between driver and object. Having in mind the excessive SSD values, at first glance this finding is not surprising.

Since increased values of object heights amendments were also found in rather broad horizontal curves, Table 1 shows, for all the examined alignments, a further investigation where the $SSD_{AVAILABLE}$ is reduced as a percentage of $SSD_{DEMANDED}$ in order the object height to retain its control value of 1.00m. For example, in order the compound alignment shown in Figure 2(b), R=1500m, Hk=13000m, to grant SSD adequacy, the demanded SSD at the most unfavourable area of the vertical curvature must be reduced by more than 32%.

***Table 1.** SSD Percentage Reduction in order Object Height to Retain Control Value of 1.00m*
*Note. CVCR values refer to entrance and exit grades of +4% and -4% respectively*

| | | CVCR (m) | | | |
|---|---|---|---|---|---|
| | | **13000m** | **20000m** | **25000m** | **40000m** |
| **R (m)** | **900** | >39% | >25% | >16% | 0% |
| | **1500** | >32% | >25% | >16% | 0% |
| | **2000** | >22% | >22% | >16% | 0% |
| | **2500** | >12% | >12% | >12% | 0% |
| | **3000** | 4% | 4% | 4% | 0% |
| | **3500** | 0% | 0% | 0% | 0% |

Therefore, from Table 1 it can be seen that by following strictly the RAA, 2008 design guidelines, in order to retain speed to 130km/h, only curves with R>3000m can be combined with the control crest vertical curvature rate of Hk=13000m.

However, many of the utilized SSD parameters provided in current practice are based either in experience or do not represent the entire passenger vehicle fleet. Aiming to point out -ready to use in practice- acceptable arrangements of compound alignments with adequate SSDs, even for cases where the $SSD_{DEMANDED}$ slightly exceeds $SSD_{AVAILABLE}$, the authors introduce the term "tolerable road length not visible to the driver". This length is defined by setting $SSD_{AVAILABLE}$ equal to $SSD_{DEMANDED}$ reduced by 9%-12%. Such a reduction was computationally determined in the present analysis by increasing the current deceleration rate of 3.7m/sec2 to 4.3m/sec2 (30), in order to incorporate improved braking performance of modern vehicles and tires (ABS, etc.). In other words, the increment of the deceleration rate to 4.3m/sec2 delivered a $SSD_{DEMANDED}$ reduction between 9%-12% depending on the grade area along the vertical curve. Based on this concept, Table 2 presents acceptable arrangements of compound alignments with SSD adequacy.

***Table 2.** Acceptable Arrangements of Compound Alignments with SSD Adequacy (V=130km/h, s==±4.0%)*

*Note: ✓ acceptable arrangements, ✓* acceptable arrangements for exit grades not bellow s= -2.5%, × unacceptable arrangements*

| | | CVCR (m) | | | |
|---|---|---|---|---|---|
| | | 13000 | 20000 | 25000 | 40000 |
| R (m) | 900 | × | × | ✓* | ✓ |
| | 1500 | × | × | ✓* | ✓ |
| | 2000 | × | × | ✓* | ✓ |
| | 2500 | ✓ | ✓ | ✓ | ✓ |
| | 3000 | ✓ | ✓ | ✓ | ✓ |
| | 3500 | ✓ | ✓ | ✓ | ✓ |

Therefore, regarding the present inner shoulder width of 0.75m, for 130km/h, in order to grant SSD adequacy, control crest vertical curvature rates of Hk=13000m can be combined with horizontal curves of R≥2500m approximately. On the other hand, the control horizontal radius of R=900m can be arranged with crest vertical curvature rates of Hk≥25000m and Hk≥30000m approximately assuming exit grades of -2.5% and -4.0% respectively.

## 6. Conclusions

In this paper, the SSD adequacy investigation carried out on left-turn curved divided highways is based on the difference between the available and the demanded SSD.

The paper is focused in examining potential safety violation for RAA, 2008 design guidelines, regarding SSD provision for 130km/h vehicle speed, on the passing lane of left curved divided highways overlapped with crest vertical curves for various horizontal and vertical design values for which the inner shoulder width is set to 0.75m.

The SSD investigation was addressed by analytical calculations in 3D for 24 different compound alignments, by pointing out the areas where the sight line is obstructed by the median barrier and delivering the non-obstructed object heights of the driver's sightline as well.

The analysis revealed that designs with control as well as near control horizontal and vertical parameters deliver extensive SSD inadequacy areas.

The authors, aiming to provide -ready to use in practice- acceptable arrangements of compound alignments with adequate SSDs, even in cases where the $SSD_{DEMANDED}$ slightly exceeds $SSD_{AVAILABLE}$ introduced the term “tolerable road length not visible to the driver” as the length of the demanded SSD reduced by 9%-12%. Such a reduction was computationally determined in the present analysis and resulted from evidence-based slight increase of the vehicles’ deceleration rate. Based on this conception, acceptable arrangements of compound alignments with SSD adequacy are delivered, and therefore a valuable tool for practitioners is delivered.

The RAA 2008 design guidelines adopt for conventional highway alignments of 130km/h design speed a constant inner shoulder width value, equivalent to the one utilized in the present analysis (0.75m). This means that the recommended horizontal-vertical alignment arrangements for such conventional high-speed highway sections with typical jersey barriers are valid for utilization in RAA design practice.

Further work is necessary in order to optimise the balance between SSD provision, other design speed values and the influence of additional parameters involved, such as the median barrier type for every utilized case (bridge or tunnel areas, interchange ramps etc.), where a more clear view of the safety margins will emerge.

Based on the recommendations of current road design practice, SSD must be provided at every point along the road surface. However, it should be noted that rather short areas with SSD inadequacy under certain conditions, might be proven acceptable. The term “short” should not be confined to solely the examined section’s length and is subject to further investigation. For example, another more comprehensive approach to be assessed in future research is to utilize reliability analysis in order to define the percentage of drivers who may have their SSD needs not met. In every case, through the present analysis, the intention of the authors is to provide a tool for practitioners to define areas with SSD inadequacy during the critical case where left-turned horizontal curves are overlaid with crest vertical curvature rates.

The parameters used in the present paper (perception - reaction time etc.) refer to daylight driving conditions. During nighttime driving, despite the fact that vehicle speeds are reported 6km/h – 15km/h less (31), the driving task remains a critical issue since the road-view geometry changes completely.

Finally, it should not be ignored that the human factor during the braking process, might impose additional restrictions and, consequently, influence the braking process.

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