MODELING STOPPING SIGHT DISTANCE ON LEFT-TURN CURVES OF FREEWAYS OVERLAPPED WITH CREST VERTICAL CURVES

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ABSTRACT

This paper investigates potential Stopping Sight Distance (SSD) violation for 130km/h vehicle speed, on the passing lane of left curved, divided highways overlapped with crest vertical curves.

The authors previously developed a SSD control methodology that relates concurrently the 3D configuration of a roadway to the dynamics of a vehicle moving along the actual roadway path, which is applied for the assessment of critical design parameters directly related to both demanded and available SSD values.

Initially, by utilizing control geometric and driver - obstacle values adopted by AASHTO 2011 design policy, excessive SSD inadequacy areas were revealed. Subsequently, on the basis of a classic statistical and explanatory modeling approach for a number of geometry parameters, an evaluation of SSD sufficiency was carried out in terms of both the probability of SSD inadequacy and the prediction of the object height in order to grant SSD adequacy (amended object height). These models may be useful to researchers and practitioners aiming to evaluate the interaction of the utilized design parameters in terms of the presence and the extent of SSD deficiency.

The results suggested that the probability modelling approach was efficient, yielding a model which enables to correctly assess SSD adequacy (by more than 94%) in such 3D road alignments. The lognormal modelling approach for the prediction of the amended object height (AOH) was proved somewhat less accurate when the AOH exceeds 1 metre, and further analysis is required in order to fully investigate the non-linear relationships between the examined variables and the amended object height.

INTRODUCTION AND PROBLEM STATEMENT

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, since in case of SSD inadequacy a usual solution is either an increase of the inner shoulder width or to a decrease of 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 problem. For example, the Green Book (1) stresses that, in order SSD provision to be granted, the vertical curve should be entirely designed inside the horizontal curve. In the 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).

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 3-D methodology similar to the present paper for measuring sight distance, utilizing triangulation methods via an algorithm consisting of three stages- road surface development, virtual field of view surface development, and virtual line of sight plane development .The process involved multiple software platforms, thus delivering an accurate but non-flexible outcome.

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.

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. 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. It is worth noting that in such alignments, the above actual grade and friction values are ignored in current practice. Therefore, by utilizing an iteration process through the laws of mechanics, the vehicle's speed reduction was determined based on the actual tire-road friction interaction. $SSD_{AVAILABLE}$, on the other hand, is termed as the driver's line of sight towards the object height, both at a certain offset in 3D roadway environment. 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 developed procedure, analytically outlined through 19 and 20, among others identifies areas of interrupted vision lines between driver and object at left-turn curves due to the presence of median concrete barriers.

Consequently, through the suggested approach, the authors aim initially in defining areas where the overlaid crest vertical curvature on horizontal curved alignments generates SSD inadequacies. Such an effort was partially addressed through a recent work of the authors (21), where, for the design speed of 130km/h and for a wide range of horizontal and vertical design values, certain arrangements of such compound alignments were precluded in terms of SSD inadequacy. However, this assessment was confined from the utilization of a single value referring to inner shoulder width. Therefore, in the present paper a range referring to the most typical inner shoulder width values is utilized as well in order to develop statistical models capable of:

- Estimating the probability of SSD inadequacy
- Predicting the additional object height in order to grant SSD adequacy (referred in the present paper as amended object height)

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, 22). The presence of median barriers on left-turn curved, divided highways, although increasing the level of safety, under certain circumstances may affect the sight distance available to drivers (23).

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, and especially the clearance between the barrier and the left edge of the passing lane, known as inner shoulder width (ISW), seems to be the most critical issues (e.g. 1, 24).

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 (22). However, in any utilized median barrier type, vehicles travelling on the opposite direction should not interrupt the driver's line of sight. Figure 1a and 1b shows a cross-section example of "New Jersey" concrete barrier type with 0.81m height, as shown in Roadside Design Guide (22).

EXISTING SIGHT DISTANCE APPROACH ON LEFT CURVED DIVIDED HIGHWAYS

Although the necessity for SSD adequacy on left-turn curves of divided highways is emphasized in current design practice (e.g. 1-4, 25), 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 (26) 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 (27). Therefore, the adoption of the conventional approach, given by the current practice, besides the cost or performance impacts, may lead to road safety violation as well, since either the widened inner shoulder potentially can be used as an extra traffic lane for passing maneuvers especially by motorcyclists, or areas with unexpected speed discontinuity will emerge.

Klam et. al. (28), 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 (29) were reached. To increase the Test Level a stabilized rail was suggested to be attached to the low-profile barrier.

In another research (30), 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. (23) 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.

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 required (23).

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 (25), 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 provisions 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.

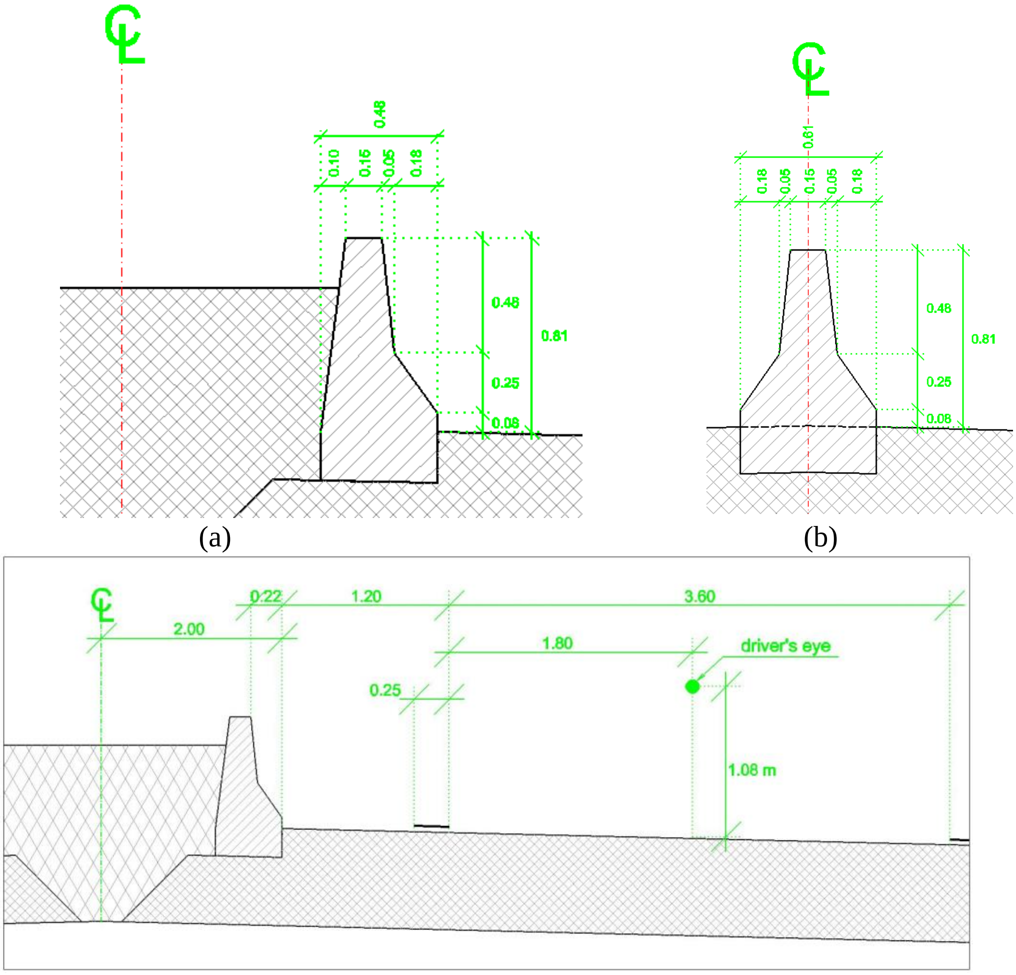
Moreover, aiming to provide a clear outlook of the interaction as well as appropriate arrangement between the horizontal and vertical alignment, none of the relevant research studies examined the impact of median barriers on SSD adequacy concurrently from the 3D alignment design viewpoint along with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

3D SSD ADEQUACY INVESTIGATION FOR AASHTO 2011 DESIGN POLICY ON LEFT CURVED DIVIDED HIGHWAYS

In order to investigate potential safety violation for AASHTO 2011 design guidelines, certain cases of left-turn curved, divided highway segments were examined. Initially, the utilized design parameters for the selected design speed of 130km/h represent control values [R=950m (horizontal radius) for e=6% (superelevation rate), K=125m (rate of crest vertical curve)]. 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.

Since, according to AASHTO 2011, the maximum grade value for 130km/h assuming rolling terrain is set to 4%, the crest vertical curve’s boundary grade values were set to -4% and 4% (symmetrical) respectively. As far as the ISW is concerned, based once again on AASHTO, values ranging from 1.20m – 2.40m were utilized.

A cross section example at the barrier area is shown through Figure 1c and consists of a passing lane and an inner shoulder of 3.60m and 1.20m respectively (AASHTO 2011). The median barrier of Figure 1c is a “New Jersey” type with height of 0.90m (0.81m plus safety margin), where its curvature at the top increases the inner shoulder by 0.22m (Figure 1c).



(a) (b)

(c)

NOTE: (a: single sided, b: double sided).

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

As far as the driver’s eye and object heights are concerned, 1.08m and 0.60m were assumed (AASHTO 2011), where the deceleration rate and the driver’s perception – reaction time were taken as 3.40m/sec^2 and 2.5sec respectively (AASHTO 2011). Finally, the lateral offsets of both driver and obstacle from the edge of the passing lane (Figure 1c) were assumed half of the lane width (1.80m).

As already stated, the sight line in median barriers should not be allowed in any case to go beyond the edge of traveled way on the opposite direction so that the available SSD would not depend on whether there is a vehicle in the opposite direction. Therefore, simple calculations (21) revealed that by utilizing the control value of R=950m, the Median Width (MW) should be 2x4m, where for R>1435m, a median width of 2x2m was used as shown in Figure 1c (note that MW≥2x1.5m for AASHTO 2011).

An example of the driver's sightline being obstructed at the barrier area of a left-turn curved divided highway is shown in Figure 2a, where three types of SSD deficiencies can be seen - the hidden sightline by the barrier area (blue line), the (max) vertical distance below the NJ area (green line), and the amended object height (red line) in order for SSD at the examined station to be granted.

The SSD adequacy assessment in the present paper, was carried out by utilizing the following stages: alignment selection; definition of calculation step (100m in the present analysis) where the driver's vehicle is positioned; calculation of $SSD_{DEMANDED}$; $SSD_{AVAILABLE}$ forced equal to $SSD_{DEMANDED}$; calculation of intersection points between the driver to object sightline and the median barriers area in 3D; record of these points in order to calculate, for the most unfavorable case, the vertical difference of the sightline from the barriers' top as well as the amended object height in order the driver's sightline to be non-obstructed due to the median barriers.

The above process initially was assessed for ISW=1.20m assuming from the horizontal alignment point of view a circular arc (R=950m), which encloses a vertical transition area (K=125m, L=1000m) arranged as to allow the examination of the braking procedure of the vehicle throughout the variable grade area (prior, during and after), thus including the constant grades as well (Figure 2b).

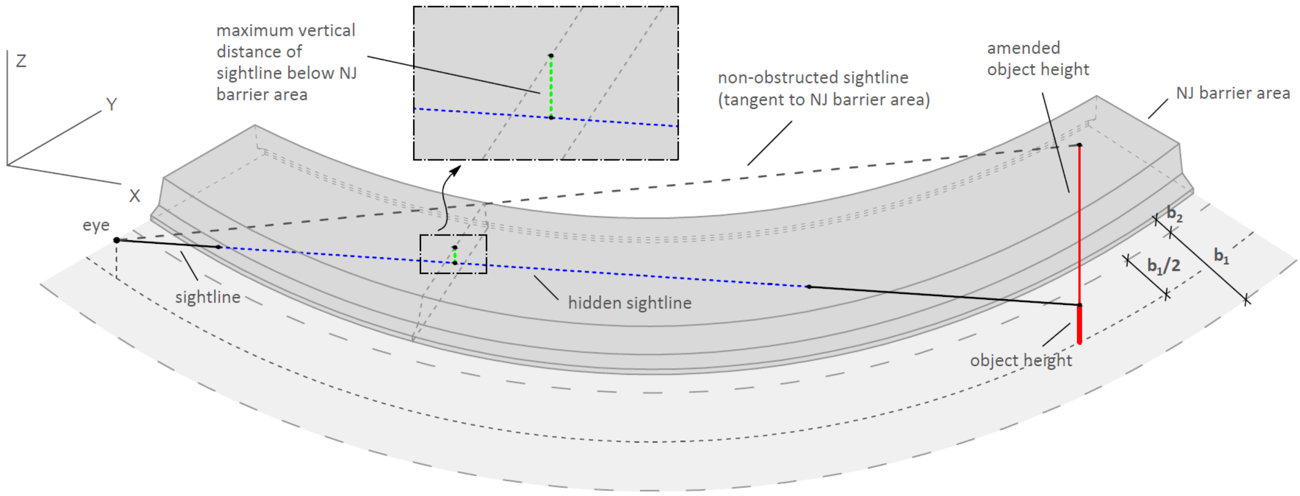
Figure 2b illustrates certain sets (14 sets) of horizontal bars (4 bars per set) where SSD adequacy was examined at fixed distances every 100m. The primary (bottom) horizontal axis shows the linear projection of the horizontal circular arc where the vertical transition area (St.1500 – St.2500) is illustrated as well. The vertical axis represents the same fixed locations (every 100m) of the examined alignment where the vehicle's SSD procedure is initiated. The bars in black color show various SSD values referring to the relevant station, where the lines in blue express the length of the driver's sight line blocked by the median width in 3D perspective. Both black and blue bars are measured through the horizontal alignment's centerline. For example at St.2000, which is located inside the vertical curve, the SSD is 292.0m and the sight line is blocked twice (St.2030 – St.2119 and St.2171 – St.2267). From the length of the SSD bars it can be seen that the assessment besides the areas of constant grade incorporates the effect of the vertical transition as well. The secondary (top) horizontal axis of Figure 2b quantifies the max vertical distance of the sightline below the New Jersey barrier (dashed green line) as well as the modified obstacle height (dashed red line) in order for the sightline to pass tangentially over the most unfavorable point. For the same Station (St.2000), it can be seen that somewhere inside the relevant two blue lines the sightline intersects the NJ barrier area 0.73m below the top, where in order to retrieve SSD adequacy, the obstacle height should be set to 2.25m.

It is evident that the points referring to the green and red line do not necessarily coincide. The evaluation was drawn assuming 0.90m as barrier height [0.81m+safety margin (plantation, construction tolerance etc.)]. It can be seen that if the barrier height for some reason is raised by 0.10m to 1.00m, the max vertical distance of the sightline below the NJ barrier area (green line) will be raised 0.10m accordingly, however not the same finding will be noticed for the new obstacle height (red line) which increases as a function of the distance from the driver's eye. As a result, assuming as barrier height the original value of 0.81m, SSD adequacy would be granted only in the constant grade area (St.1200 and St.2500 respectively).

In Figure 2b the most critical SSD inadequacy area is found in the negative grade area and close to the end of the vertical transition (St.2200), where the obstacle height should be raised up to 2.44m in order to be visible.

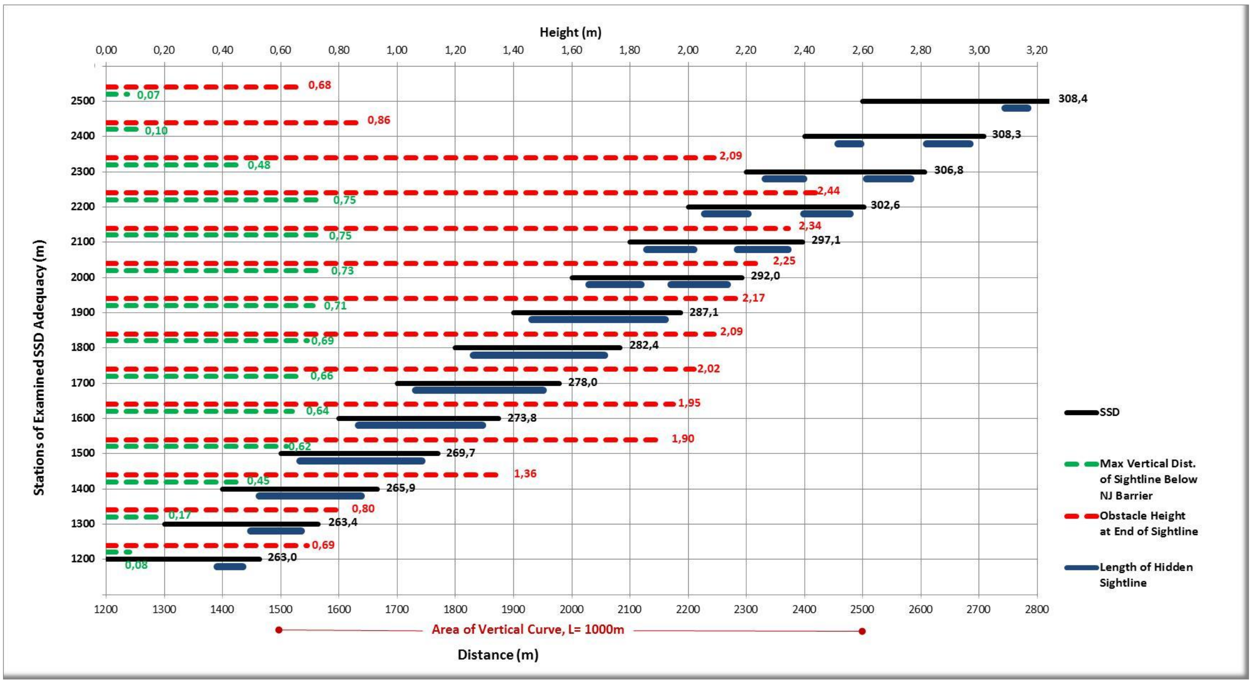
Commenting further on Figure 2b, it can be seen that AASHTO 2011 design guidelines fail to warrant safety during emergency braking of a vehicle moving with 130km/h on the passing lane of such a left curved divided highway geometry, since the median barrier obstructs the line sight between driver (1.08m) and object (0.60m) heights. At first glance this finding is not surprising since by applying basic geometric considerations the barrier height (0.90m) is greater than the average heights between the driver and the obstacle. Moreover, this assumption overestimates the actual available SSDs on curved horizontal sections overlapped with crest vertical curves (5).

From the above process it can be seen that although SSD adequacy can be accurately calculated for any arrangement, the analytical model is computationally demanding. Moreover there is a clear need for practitioners to be informed in advance regarding the interaction of the utilized design parameters selection in terms of SSD adequacy.



Note: b_1: passing lane, b_2: inner shoulder width.

(a)



(b)

FIGURE 2 SSD Adequacy Investigation on Compound Alignment of Left Curved Divided Highway (R=950m, K=125m, ISW=1.20m, All Possible Arrangements Examined).

MODELS DEVELOPMENT

In several recent studies (e.g. 30, 31) probabilistic approaches, such as simulation and reliability analysis, are proposed as an appealing option for identifying SSD inadequacy patterns. In this paper, an interpolation approach on the basis of key SSD critical situations is proposed instead to provide a simple, generic and flexible tool for the assessment of SSD adequacy. More specifically, SSD is modelled in terms of evaluating the probability of SSD inadequacy and predicting the amended object height in case of SSD deficiencies. Regarding the first case, a logistic regression model is developed for the estimation of the probability of the required SSD exceeding the relevant available, where an amendment of the object height is inevitable. In the latter case, the amended object height itself (i.e. the increment of the object height over the control value of 0.60m) is estimated on the basis of the road geometric design elements in 3D context.

The main explanatory variables considered include the horizontal (R) and vertical (K) curvatures , the grades (s1, s2) which refer to the starting and ending grade values of the braking procedure, their difference (ds), as well as the inner shoulder width (ISW). More specifically, for the initially selected calculation step (100m), the grade value s1 was calculated based on the selected vertical curvature (K). The ending grade value of the braking process (s2) was calculated as a function of the selected horizontal (R) and vertical (K) curvatures' explanatory variables By equalizing $SSD_{AVAILABLE}$ to $SSD_{DEMANDED}$ and utilizing the selected ISW value outputs similar to Figure 2b were delivered. A number of alignment arrangements were formed by combining the following variables:

- Horizontal radii values (950m, 1500, 2000m, 2500m, 3000m, 3500m)
- Vertical curvature rates (125m, 200m, 250m, 300m, 350m, 400m)
- ISW (1.20m, 1.80m, 2.40m)

In other words, for every possible arrangement of the above variables, graphs similar to Figure 2b were extracted resulting from the performed SSD adequacy investigation in advance, along, and beyond the vertical transition area, formed by the grade values of +4% and -4% respectively. In total, 2772 different alignment cases were examined.

In order to enhance the explanatory performance of the models, selected interactions of these variables were also tested on the basis of the insights already obtained by the implementation of the analytical approach. Moreover, specific conditions were addressed by means of dedicated variables in order to capture not only the core cases along the main curve (e.g. non linear relationship between horizontal curve radius and SSD inadequacy) but also the marginal cases at the boundaries of the curve (e.g. at the constant grade section).

A likelihood ratio test was used to assess model quality, and the quality of the predictions was the ultimate criterion for selecting the optimal model.

Logistic Regression Modelling of the Probability of SSD Inadequacy

The specification of the SSD inadequacy model is given by Equation 2 , with π_{ij} the probability of SSD inadequacy, X_i the explanatory variables, β_i parameters to be estimated and ε_i the logistically distributed ~[0, μ] error term, as follows:

$$Logit(\pi_{ij}) = Log\left(\frac{\pi_{ij}}{1-\pi_{ij}}\right) = \sum \beta i Xi + \varepsilon i \qquad (2)$$

In particular, the logit link function expresses the logarithm of the odds of SSD inadequacy, i.e. the logarithm of the ratio of the probability of SSD inadequacy to the probability of SSD adequacy. A binary logistic regression model is fitted to the data.

The parameter estimates, their marginal effects (Exp(B)), their elasticities and goodness-of-fit measures of the best fitting model are presented in Table 1a. It is noted that, while marginal effects Exp(B) express the change in the odds of SSD inadequacy for 1 unit increase of the explanatory variable, elasticities express the related % change in the odds for 1% increase of the explanatory variable; in this sense, elasticities are easier to interpret, as they are dimensionless and unconditional to the measurement units of explanatory variables. The final model is shown through Equation 3 as follows:

$$Logit(\pi_{ij}) = Log\left(\frac{\pi_{ij}}{1-\pi_{ij}}\right) = 0.18*K + 0.009*R - 0.162*s1 - 11{,}568*Ds - 5.15*ISW - 0.002*R2 - 0.008*K*Ds + 0.004*R*Ds - 0{,}00000705*K*R + 0.782*Ds*s1 + \varepsilon i \quad (3)$$

This model can be analysed as follows: on one hand, there are variables referring to all the examined alignments, i.e. R, s1, ISW; and on the other, there are variables and interactions concerning alignments within a vertical curve, i.e. K, ds, K*ds, R*ds and s1*ds. Obviously, when ds equals zero, the model describes alignments on constant grade values of +4% or -4%.

The parameter estimates of the main effects suggest that an increase of the vertical curvature increases the probability of SSD inadequacy. More specifically, the elasticity indicates that a unit increase in vertical curvature rate increases the odds of SSD inadequacy by more than 3 times (3.4). On the basis of the insights from the analytical estimation, a quadratic form of the effect of horizontal curvature was considered, and the results confirmed this specification, as the parameters of both R^2 and R were statistically significant. In particular, the parameter of R is positive (elasticity equals 1,51 i.e. 151% increase of the odds of inadequacy for each 1% increase of R) and the parameter of R^2 is negative, which corresponds to a parabola, i.e. as R increases, the probability of SSD inadequacy initially increases up to a certain point, from which the probability of SSD deficiency decreases. These findings were also noticed from a previous research of the authors (21).

On the other hand, an increase in the ISW decreases the probability of SSD inadequacy, by 68% per 1% increase (elasticity equals -0,680). Moreover, an increase in grade at the beginning of the braking procedure (s1) and an increased difference between the grades at the starting and ending points of the braking procedure (ds)[1] decrease the probability of SSD inadequacy by 0,8% and by 62%, per 1% increase respectively. In other words, the negative grade area of the vertical curve is more critical in terms of SSD inadequacy due to the increase of the demanded SSD.

The interactions suggest that the combined effect of vertical curvature and grade difference decreases the probability of SSD inadequacy, while the other combined effects (i.e. horizontal curvature and grade difference, horizontal and vertical curvature, grade at the beginning of the breaking procedure and grade difference) increase the probability of SSD inadequacy.

The likelihood ratio test leads to accept the model compared to the null model, and a pseudo R-squared (estimated as 1-LL/LL0) (*32*) is equal to 0.79, which is very satisfactory for this type of model. In fact, logistic regression models may have an upper limit lower than 1 in the maximum R-squared value that can be achieved, due to the likelihood-based estimation instead of ordinary least squares estimation, as well as to the nature of the response variable (*32*, *33*).

Table 1b summarises the classification of cases on the basis of the model predictions. More specifically, the Table presents a cross-classification of observed and predicted values for

[1] It is noted that (ds) takes negative values, and consequently the elasticities of parameters including (ds) may have different sign from the parameter estimates B, as the elasticities are calculated on the basis of the product of B (negative) with (ds) (also negative).

the dependent variable (i.e. probability of SSD inadequacy); for a perfectly fitting model, one would expect the observed and predicted values to match (see highlighted parts of the table) and the off-diagonal cells of the Table would be empty. The Table data reveal that more than 94% of total cases are correctly classified by the model as regards SSD adequacy. The 155 cases [75+80, (Table 1b)] of falsely classified cases - i.e. cases of observed inadequacy (value=1) which are predicted as cases of adequacy (value=0) or vice versa - were carefully reviewed in order to identify potential systematic failure of the model to capture particular cases. It was observed that no systematic misclassification was identified. However, it was noticed that 51 misclassified cases - a share of approximately 33% of the 155 misclassified cases - (i.e. about 2% of all cases) involves alignments of constant grade (either -4% or +4%) - although, the majority of the cases of alignments of constant grade were correctly classified by the model. It was examined whether a more detailed specification of variables referring to the constant grade alignments (e.g. entering s1=-4% as a distinct variable) may enhance the model but no significant improvement was observed.

Lognormal Regression Modelling of the Amended Object Height

The specification of the amended object height (AOH) model was determined on the basis of a thorough descriptive analysis of the data revealing nonlinear associations of amended object height (i.e. the increment of the object height over the control value of 0.60m) with the examined variables. A histogram of the response variable led to the identification of a clearly skewed density function, suggesting a lognormal distribution (Equation 4). Consequently, with X_i the explanatory variables, β_i parameters to be estimated and εi the normally distributed ~[0, σ^2] error term, this lognormal model is formed as follows:

$$Log(AOH_i) = \sum \beta i X i + \varepsilon i \qquad (4)$$

The parameter estimates and goodness-of-fit measures of the best fitting model are presented in Table 1c. The final model specification is as follows (Equation 5):

$$Log(AOH_i) = 1.117 - 0.002*K - 0.003*R - 0{,}768*ISW - 0.772*Ds + 0{,}0000008*K*R - 0.005*K*Ds - 0{,}0002012*R*Ds + {,}0002100*R*ISW - 2.499*(s14) + 0.002*R*(s14) + \varepsilon i \qquad (5)$$

Similar to the previous case, this model can be analysed, based on variables and interactions for all the examined alignments (i.e. R, s1, ISW, R*ISW) or specifically for alignments within a vertical curve (i.e. K, ds, K*ds, and R*ds). In the latter case, a variable specific to the case where s1=s2=-4% (s14 in Table 1c) and its interaction with the horizontal curvature were found to be significant. Furthermore, a quadratic function of horizontal curve radius was tested but was not found to outperform the logarithmic function with respect to amended object height.

The parameter estimates of the main effects suggest that an increase in all main effects (i.e. K, R, ISW, ds, s14) decrease the amended object height, while all the interactions increase the amended object height, except from K*ds which decreases the amended object height. The likelihood ratio test leads to accept the model compared to the null model, and a pseudo R-squared is equal to 0.71, which is satisfactory.

A closer look at the predicted values suggest that the differences between observed and predicted values are low; however, the model residuals are not white noise (i.e. unrelated to the predicted values), and the plot of residuals against the predicted values suggests the presence of a more complex non-linear relationship. In particular, an area of poor model performance was identified with respect to cases where the observed amended object height exceeded 1m beyond the control value of 0.60m.

TABLE 1 (a) Parameter estimates and goodness-of-fit of the logistic regression model of SSD inadequacy
(b) Classification of the Logistic Regression Model (observed vs. predicted SSD inadequacy)
(c) Parameter Estimates and Goodness-of-Fit of the Lognormal Regression Model of the Amended Object Height

(a)

Parameter	B	S.E.	Wald test	p-value	Exp(B)	Elasticity
K	,01813703	,00295862	37,580	<0,001	1,018	3,404
R	,00875999	,00064639	183,663	<0,001	1,009	1,516
s1	-,16167454	,05077569	10,138	,001	,851	-0,009
Ds	-11,56791068	1,42435424	65,959	<0,001	,000	0,617
ISW	-5,15025730	,31647009	264,845	<0,001	0,006	-0,680
R^2	-,00232342	,00020009	134,829	<0,001	0,998	-1,006
K * ds	-,00765764	,00269050	8,101	,004	,992	0,115
R * ds	,00375407	,00048204	60,651	<0,001	1,004	-0,513
K * R	-,00000705	,00000127	30,590	<0,001	1,000	-3,25
ds * s1	,78238421	,08736706	80,195	<0,001	2,187	-0,036
Null Log-likelihood (LL0)		-1864,85				
Final Log-likelihood (LL)		-392,825				
Likelihood Ratio test		2944,05				
df		10				
pseudo R-squared		0,79				

(b)

SSD inadequacy		**Predicted**		**% Correct**
		0	1	
Observed	0	1032	75	93,2
	1	80	1585	95,2
Total				94,4

(c)

Parameter	B	Std. Error	Wald Chi-Square	p-value
(Intercept)	1,1172864	,2487440	20,175	<0,001
K	-,0024194	,0003363	51,754	<0,001
R	-,0029807	,0001715	301,972	<0,001
ISW	-,7683734	,0546478	197,697	<0,001
Ds	-,7717293	,0748511	106,300	<0,001
Kx R	,0000008	,0000002	23,110	<0,001
K * ds	-,0053688	,0002712	391,984	<0,001
R * ds	-,0002012	,0000362	30,832	<0,001
R * ISW	,0002100	,0000310	45,802	<0,001
[s14=,00] * R	-2,4985374	,2694198	153,768	<0,001
[s14=1,00] * R	0		.	.
[s14=,00]	,0022574	,0001820	86,003	<0,001
[s14=1,00]	0		.	.
(Scale)	,1259748[b]	,0043661		
Null Log-likelihood		-2198,8		
Final Log-likelihood		-637,8		
Likelihood Ratio test		3122		
df		10		
pseudo R-squared		0,71		

It is clear that the final model specification may not address all possible combinations of design parameters with the same accuracy and the logarithmic model is certainly an approximation. However, even with this imperfect specification, the model can be useful within a preliminary assessment of the design parameters as regards SSD adequacy.

CONCLUSIONS

The research is focused in examining potential safety violations for AASHTO 2011 design guidelines, regarding SSD provision for 130km/h vehicle speed, on the passing lane of left-turn curved, divided highways overlapped with crest vertical curves for various horizontal and vertical and inner shoulder width design values.

Initially, SSD adequacy investigation was addressed through analytical calculations for control horizontal and vertical design values, where extensive SSD shortage zones were revealed inside the area of the horizontal radius.

Subsequently, an evaluation of SSD sufficiency was carried out in terms of both the probability of SSD inadequacy and the prediction of the amended object height.

The proposed statistical modelling approach may have a twofold interest. Firstly, although SSD adequacy can be accurately calculated for any arrangement, the analytical model is computationally demanding and there is a need for an efficient and applicable tool. Secondly, emphasis is given not only on the identification of the effects of road design elements on SSD adequacy, but also on the quantification of these effects (i.e. elasticities), which consists a very useful tool for practitioners. For example, a researcher or practitioner may test his or her design parameters by implementing the logistic regression model equation, and obtain the probability of SSD adequacy and the related classification of this set of design parameters (i.e. adequacy or not). In case inadequacy is predicted, the researcher or practitioner may further implement the lognormal regression model to obtain a prediction of the AOH, which allows for some insight whether the set of design parameters needs small adjustment (e.g. small AOH) or significant adjustment (e.g. large AOH), and therefore reassess the utilized design parameters accordingly.

Nevertheless, the proposed explanatory approach is not without limitations, due to the complex yet deterministic nature of the relationships examined, inducing an obvious risk of overfitting the statistical models and thus yielding measurement errors in the effects identified. The challenge of the proposed approach was to develop models able to efficiently capture the key determinants of SSD adequacy and estimate SSD adequacy at a high accuracy level, so that the models may be useful to researchers and practitioners dealing with road design assessment. In that sense, model parsimony was not a priority, to the extent to which model quality and performance are not compromised.

The results suggest that the probability modelling approach was efficient, yielding a model which enables researchers to correctly classify SSD adequacy in such 3D road alignments. The logarithmic modelling approach of the AOH prediction is somewhat less accurate, and further analysis is required in order to fully investigate the non-linear relationships between the examined variables and the AOH. In this framework, non parametric and machine learning methods (e.g. neural networks) may be proved efficient in capturing these complex and non-linear relationships.

Further analysis should also aim at the cross-validation of the models, particularly as regards the unfavorable conditions, through the use of separate training and testing datasets.

Finally, additional work is necessary in order to examine more speed values, but mostly optimize in terms of SSD provision, the influence of additional parameters involved. Such parameters comprise the median barrier type for certain cases (e.g. bridge or tunnel areas, interchange ramps etc.), issues associated to human factors, more realistic deceleration values, as well as night time driving conditions where a more clear view of the safety margins will emerge.

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