



16th Road Safety on Four Continents Conference
Beijing, China 15-17 May 2013

STUDY OF INFLUENCE OF BARRIERS ON VISIBILITY OF TWO-WAY HIGHWAYS

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ABSTRACT

Stopping Sight Distance (SSD) must be guaranteed the entire length of a highway. However, elements of the cross-section in the design can interfere with sight distances. This can be the case when barriers, rather than medians, are used on two-way highways, especially along left curves. Thus, this study analyzed the position of barriers in a hypothetical scenario using graphic three-dimensional simulations. The lateral offset of the barrier relative to the roadway was defined according to each design speed and radius of the horizontal curve was analyzed. The results of the simulation were compared with the model, which was found in Brazilian guides, for offsetting fixed objects from horizontal curves. The differences found in this study demonstrated the viability of the method used, and the project was considered useful as a whole because it was developed in a three-dimensional fashion.

1 INTRODUCTION

Visibility conditions for a driver are one of the most critical factors for the safe and efficient operation of a vehicle (DER-SP, 2006; García and Belda-Espluglues, 2007). In developing a project, visibility should be used to define parameters, design the road, and validate the road's quality. With an adequate visibility distance, the driver is able to acquire data about the road and traffic, interpret the data, set the vehicle to the appropriate trajectory and speed, and make decisions quickly and safely, including stopping the vehicle or performing other types of maneuvers when faced with an unexpected obstacle (DER-SP, 2006).

Elements of the cross-section, however, can interfere with visibility distance. This is the case when barriers are used instead of medians on two-way highways. Barriers are used as a safety device, but a barrier can obstruct visibility on the highway when it is inappropriately positioned, thereby reflecting a poor design. Therefore, the barrier's position should be compatible with its function of safety while maintaining visibility conditions on the highway without adding risks for the driver.

Leisch (1989) notes that the use of concrete barriers on highways can generate inadequate stopping sight distances (SSDs), primarily along curves and in areas near bridges or tunnels. According to Leisch, a solution would be to increase the spacing between the road and the barrier, with each case being analyzed individually for an optimal solution that does not compromise visibility and safety on the road. AASHTO (2004) and Arndt (2010) have expressed reservations about increasing the space. If the spacing between the road and the barrier is greater than 3.6 m, there is a possibility that it will be used by cars to pass or as

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another lane. In these cases, the function of this area becomes ineffective relative to its initial purpose.

In this context, the aim of this study was to investigate the position of rigid barriers such that they do not interfere with the visibility distance required by drivers along a specific highway. The scenario chosen for analysis included sections of left turns, where barriers have a greater probability of obstructing visibility. Aspects of the barrier's safety features, such as design and construction material, were disregarded. In this study, a computer graphics tool was used to generate hypothetical scenarios.

2 THEORETICAL FOUNDATION

2.1 Stopping Sight Distance

In geometric designs, visibility is related to measurable distances: stopping sight distance (SSD), passing sight distance (PSD), and decision sight distance (DSD). SSD has a required minimum value that must be met at any point on the highway (Lamm, Psarianos, and Mailaender, 1999; AASHTO, 2004). The other two distances have recommended values that when met raise the technical standards of the road. In this study, only SSD was considered because it is a primary condition for guaranteeing the visibility conditions of a road.

SSD is described as the sum of two other distances: (1) the distance traveled by the vehicle from the moment the driver sees an obstacle requiring it to stop to when the driver engages the brake system (reaction distance) and (2) the distance traveled by the vehicle from the moment the brakes are activated to when it reaches a complete stop (braking distance). Therefore, SSD is expressed as the sum of two parts:

$$SSD = d_1 + d_2 \quad (1)$$

in which d_1 : perception and reaction distance, and
 d_2 : braking distance.

Reaction distance (d_1) is usually defined as a function with only two parameters: the design speed and the perception and reaction time. Brazilian standards have adopted a value of 2.5 s in accordance with AASHTO (2004). The second part of SSD, braking distance (d_2), has a greater range of variation, and the parameters of the design can also be considered parameters of the vehicle. The formula used in this work to calculate SSD is also used by AASTHO (2004) and DER-SP (2006) in which

$$SSD = 0,278 \times V \times t + \frac{V^2}{254 \times \left(\left(\frac{a}{9,81} \right) + i \right)} \quad (2)$$

where: SSD : Stopping Sight Distance (m),
 V : Velocity (km/h),
 t : Perception and reaction time (s),
 a : Deceleration rate (m/s^2), and
 i : Longitudinal slope of the road (%).

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The rate of deceleration is constant and equals 3.4 m/s^2 . Based on the formula above, the DER-SP shows minimum values for SSD, assuming wet pavement and that travel speed equals design speed (Table 1), which are values that were adopted in this study.

Table 1: Minimum SSD values for a road design (m).

Velocity (km/h)	Slope of ramp		
	-6%	0%	6%
50	70	65	59
60	92	85	77
70	116	105	97
80	144	130	118
90	174	160	141
100	207	185	167
110	243	220	194
120	281	250	223

SOURCE: Adapted from DER-SP (2006).

The Manual for Geometric Design of Rural Roads (DNER, 1999) presents formulas for SSD that consider tire pavement friction as a factor instead of the deceleration rate, as in AASHTO (2004) and DER-SP (2006). Furthermore, this Brazilian manual considers two possibilities when calculating SSD: using average speed and using design speed. The first possibility produces the minimum values of SSD to be met. However, because drivers tend to drive at a speed close to the design speed, the standard offers an alternative in which SSD is a function of design speed. Figure 1 shows SSD values for both possibilities offered by DNER and the value considered in this study assuming no slope. The adopted formula assumes minimum values for SSD that are between the two possibilities from DNER (1999).

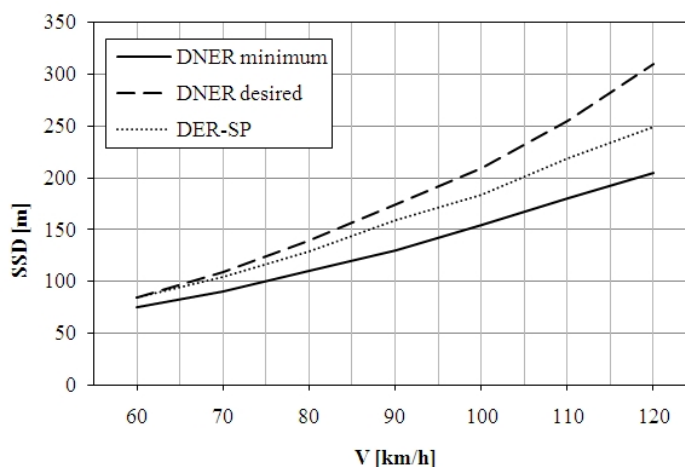


Figure 1: Comparison of SSD values from DNER and DER-SP.

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Finally, visibility checks need to consider that a driver must see an object at a given distance along the entire road. The analysis must consider (a) a measurable distance (in this case, the SSD), (b) the driver's position, and (c) characteristics of the observed object. A height of 1.080 m was adopted as the driver's eye level (AASHTO, 2004; DER-SP, 2006; DNIT, 2010). DNER (1999) recommends an object height of 0.15 m or greater when analyzing SSD. In this study, we used 0.60 m as the object height, corresponding to the average height of a vehicle's tail lights, which, according to AASHTO (2004), is the height at which an object poses risks to a vehicle.

2.2 Visibility *versus* rigid barriers

The design manual from DNER (1999) gave the following definition of a barrier:

“Rigid structure, not capable of being deformed, generally concrete, arranged along the road to prevent runaway vehicles from leaving the platform, collisions with fixed objects, invasions adjacent lanes, and, hopefully, reorients the vehicle to its correct path with minimal damage to the driver and passengers. Also called rigid physical separator.”

Thus, by definition, a barrier is a safety device for the road. Additionally, a barrier can be used as a physical separator, generally in cases in which it is not possible to have central medians because of limitations of the road platform or in cases of duplication of the roads. In both situations, the barrier becomes one of the project's features, although one that occurs alongside the road and thus may become an obstacle to visibility. Leisch (1989) was among the first to indicate this problem, which occurs mainly on turns. Two decades later, studies concerning this subject are still scarce. Sanchez (1994) performed a study on visibility and barriers by creating digital models of the sections under study. Recently, Arndt (2010) posed new questions about possible alternatives, including a solution to the parameterization flexibility in SSD by assuming less conservative values when barriers are present.

3 VISUALIZATION, MODELING, AND ANALYSIS OF VISIBILITY

Geometric designs include horizontal profiles, vertical profiles, cross-sectional profiles, and longitudinal profiles along the length of the road. Because of this separation, it is difficult to visualize the entire project and to consider the technical peculiarities and their influence on the environment. Techniques for three-dimensional visualization and modeling overcome these difficulties by allowing designers to objectively see the final project. In the field of transportation engineering, visualization can be understood as a static representation or simulation of real conditions or proposed alterations. Such visualization also presents the associated impacts on the surroundings as a method to show the geometric realities of the developing project and the real extent of improvements (NCHRP, 2006). Furthermore, the use of modeling helps with decisions about route changes to ensure the best technical and aesthetic qualities in the road designs (Hixon III, 2007). Furthermore, engineers must always consider the 3D highway appearance to achieve a road safety during the road design (Kanellaidis and Vardaki, 2011).

This work was based on graphical tools which results obtained through a geometrical model and not using analytical equations as showed in Wang and Liu (2010). This approach is found in various studies that analyze visibility, as observed in Sanchez (1994); Janikula and

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Garrick (2002); Han, Middleton, and Clayton (2006); Kuhn and Jha (2010); and Chou et al. (2010). For example, Ali, Easa e Hamed (2009) created analytical models to check SSD from 3D models to eliminate the need for the graphical procedure in checking sight distance adequacy. The difference is the possibility of understanding the project as a whole and check how the design elements relate to each other. Moreover, in analyzing visibility, it is possible to determine whether SSD is guaranteed along the section being analyzed by measuring the range of area without obstructions and, when appropriate, indicating areas that impede a driver's field of vision.

4 METHODOLOGY

Initially, arbitrary road projects were created for computer analysis. In this way, the real characteristics of a highway were reconstructed in a virtual environment where it can possible to control modifications and alterations of parameters for the purposes of this study. The ease of changing a parameter in the design phase as a response to specific requirements, and thereby reducing the impact of alterations on the design, was a result of choosing graphical simulation. Figure 2 shows examples of graphical simulations.

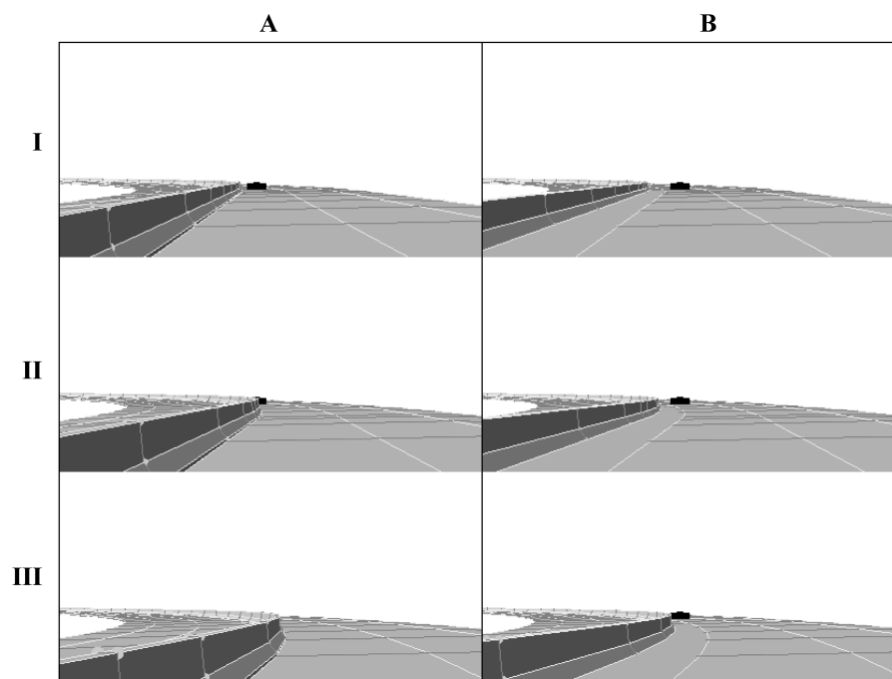


Figure 2: Example of computer simulations for studying visibility.

Figure 2 shows the visualization of the object in black at a necessary distance, the SSD, in three instances (I, II, and III) during the transition from a tangential section to a curvilinear section for two designs (A and B) with different cross-sections. Ideally, the object is observed at any point along the trajectory, which guarantees SSD throughout the section studied. In case (A), the object disappears from the field of view in (III-A), which indicates a flaw in the

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design. With a small change in cross-section in (B), that is, shifting the barrier to the left, the driver sees the object and the visibility problem is solved (III-B). Alternative solutions to the problem include reducing the speed on this section, changing the radius, and altering the road. In this study, the only change considered was the spacing between the barrier and the road to determine an optimal position that guarantees SSD along the entire road.

4.1 Hypotheses

To construct scenarios for study, the following hypotheses were formed:

- *Highways for study*: Two-way highways of classes 0 and I-A, as defined by DNER (1999).
- *Design speed*: Values for design speed and SSD according to Table 1
- *Geometry*: Horizontal curves to the left, with a radius ranging from 200 m to 2000 m and zero slope (0%: plan.) Ideally, there is agreement between the horizontal and vertical curves because the condition of zero slope is adopted as a simplification. In addition, the minimum radius of a horizontal curve was used for each velocity analyzed, being defined as

$$R_{min} = \frac{V^2}{127 \times (f_{max} + e_{max})} \quad (3)$$

where R_{min} : Minimum radius of horizontal curve (m),
 V : Design speed (km/h),
 f_{max} : Lateral tire-pavement friction, and
 e_{max} : Maximum permissible superelevation.

Maximum permissible superelevation (e_{max}) in this study was equal to 8%, which was compatible with the highway class chosen. Values for lateral tire-pavement friction were assumptions from DNER. Therefore, by knowing the maximum permissible superelevation and lateral tire-pavement friction, we could determine the minimum radius for horizontal curves for each velocity studied (Table 2) and thereby define the minimum values of radii used in this study (in multiples of 100).

Table 2: Adopted values of minimum radius for horizontal curves.

V (km/h)	60	70	80	90	100	110	120
f_{max}	0.15	0.15	0.14	0.14	0.13	0.12	0.11
e_{max}	8%	8%	8%	8%	8%	8%	8%
R_{min} calculated (m)	125	170	230	290	375	475	595
R_{min} adopted (m)	200	200	300	300	400	500	600

- *Cross-section*: Two lanes in each direction that are divided by a rigid barrier. This variable is relative to the inner edge of the roadway. In cases where the radius of the horizontal curve is greater than the minimum radius, it is necessary to scale the superelevation because centrifugal acceleration decreases and there is no need to adopt the maximum superelevation value (which occurs with the minimum radius). The hypothesis considered was to reduce the superelevation values gradually because of the increase in the radius to reach a

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minimum accepted value of 2% to facilitate rainwater drainage along the road. Therefore, the superelevations were calculated by

$$e = e_{max} \times \left(\frac{2 \times R_{min}}{R} - \frac{R_{min}^2}{R^2} \right) \quad (4)$$

where e : Superelevation to be adopted,
 e_{max} : Maximum admissible superelevation,
 R : Radius of horizontal curve (m), and
 R_{min} : Minimum calculated radius of horizontal curve relative to e_{max} for design speed (m).

- *Barriers*: New Jersey barrier with a height of 1.00 m.

4.2 Structuring the simulation process

The software AutoCAD Civil 3D 2011 was used in the simulation phase. The goal was to define lateral spacing values of the barrier relative to the edge of the roadway such that SSD is guaranteed along the entire highway. Simulation development followed a specific procedure, as defined by the following algorithm:

where Δ : constant increase (0.05 m),
 a_L : Lateral offset of the barrier (m),
 $V(k)$: Design speed and $V(k_{max})$ maximum speed (km/h), and
 $R(j)$: Radius of horizontal curve and $R(j_{max})$ maximum value of radius (m).

Step 1. Generation of Digital Terrain Model
Step 2. Generation of Digital Road Project Model
Step 3. Make $j = 1$
 $k = 1$
Step 4. $a_L(k, j) = 0$
When $V(k) \leq V(k_{max})$
If SSD is satisfied
Input $a_L(k, j)$
Make $k = k + 1$
Otherwise
 $a_L(k, j) = a_L(k, j) + \Delta$;
End If
End When
Step 5. If $R(j) < R(j_{max})$
Make $j = j + 1$
 $k = 1$
Return to Step 4
Otherwise
End simulation
End If

As a result, a matrix of values is generated in which the lateral offset of the barrier a_L is defined as a function of the design speed V and the radius of the horizontal curve R .

5 RESULTS OF SIMULATIONS

Creating an arbitrary terrain model was necessary for the simulation process and was neglected in later analyses because the obstruction factors were found only in the geometric design without including slopes or other changes in the landscape. Relative to the road path, the project extended approximately 3 km and comprised two fixed tangents. The curves that were analyzed were suitable for these tangents without adding transition curves. Arbitrary metric system for coordinates and orientation was adopted. The interests in the relative position of features in the road project instead of the real position of them.

The threshold value for defining the lateral offset of the barrier was 2.5 m during the simulations, which was a value smaller than the 3.6 m suggested by AASHTO (2004), which represents the point of view of road construction. The accuracy for each placement was ± 0.05 m. SSD was verified every 10 meters along the section studied.

The matrix for the lateral offsets of the barrier in the scenario generated 86 values, which were organized in a diagram (Figure 3). The curves for each design speed behaved similarly: as the radius of the horizontal curve decreased, the value of lateral offset of the barrier approached a maximum value and subsequently decreased. The difference in the curves was observed at the maximum points, which varied depending on the design speed in an ordered fashion (greater spacing for higher design speed) but were no higher than the limit of 2.5 m. An explanation for the decrease in the curves is that the height of the driver's eyes relative to the object increases because of an increase in superelevation (caused by the decrease in the radius of the horizontal curve), which, in turn, raises the object relative to the barrier. This geometric composition makes it possible to view over the barrier when the driver is on the inside of the curve.

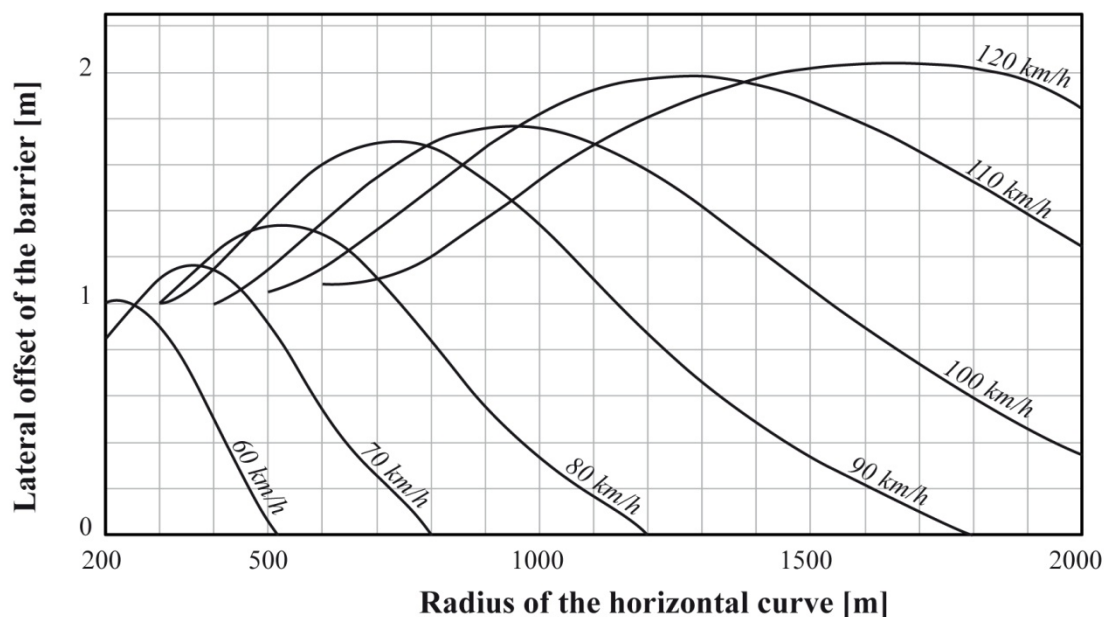


Figure 3: Diagram showing Lateral offset of the barrier relative to the radius of the horizontal curve and design speed in a hypothetical scenario.

6 COMPARATIVE ANALYSIS

Several manuals and standards present parameters for the spacing of fixed objects on horizontal curves (AASHTO, 2004; DNER, 1999; DER-SP, 2006). Thus, there is no need to simulate the position of the barrier because there are already models for this. However, the main limitation of these models is that they address visibility in two-dimensional space. A three-dimensional space in which the design is actually developed is neglected, and the models are simplified. Therefore, this paper suggested integrating the three-dimensional portion of the project in the analysis of interference visibility. The results obtained from the simulations were compared with these other models to determine the viability of analyzing the visibility in three dimensions. The model used for comparison was found in Brazilian manuals (DNER, 1999; DER-SP, 2006), as shown in Figure 4.

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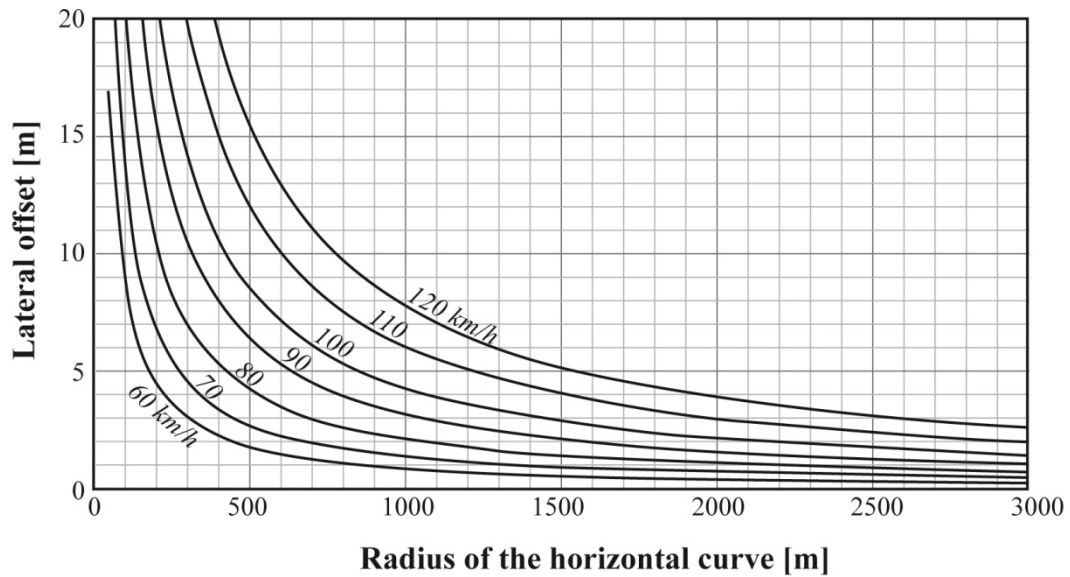


Figure 4: Lateral offsets of fixed objects in curves (M) for design speeds of 60 to 120 km/h.
SOURCE: DER-SP (2006).

The model shown in Figure 4 is summarized by the following equation:

$$M = R \left(1 - \cos \frac{SSD}{2R} \right) \quad (5)$$

where M : Lateral offset of fixed objects in curves (m),
 SSD : Stopping Sight Distance (m), and
 R : Radius of horizontal curve (m).

The formula considers spacing relative to the trajectory of the vehicle. In the simulations, spacing is measured from the outer edge of the road inside the turn. Therefore, a change in reference was necessary. Figure 5 shows the parameters involved in the transformation.

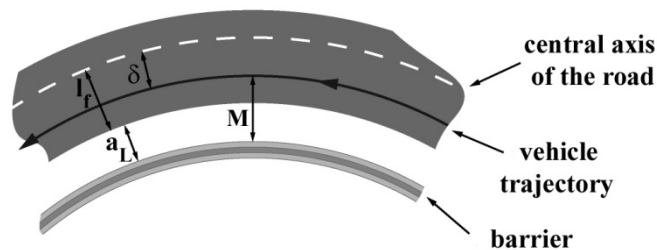


Figure 5: Parameters involved in transformation of reference.

where M : Lateral offset of fixed objects in curves (m),
 l_f : Width of road (m),

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δ : Position of vehicle's trajectory relative to central axis of the road (m), and
 a_L : Lateral offset of barrier (m).

Using algebra, it is possible to express the value of M as a function of a_L because the other parameters are known. The width of the road was 3.6 m, and the trajectory traveled by the vehicle was shifted 2.0 m from the central axis of the road. The following relationship is defined:

$$a_L = M - 1.6 \text{ m} \quad (6)$$

Thus, it is possible to calculate spacing using equation (5) and to compare this value with those found in the simulated scenario. Table 3 shows statistical parameters, and Figure 6 gives a graphical representation. Both Table 3 and Figure 6 represent the differences between the simulation and model.

Table 3: Statistical parameters of differences between the simulation and model.

Average (μ)	-1.91 m
Standard Deviation (σ)	± 2.47 m
Smallest Difference	-0.10 m
Greatest Difference	-10.23 m

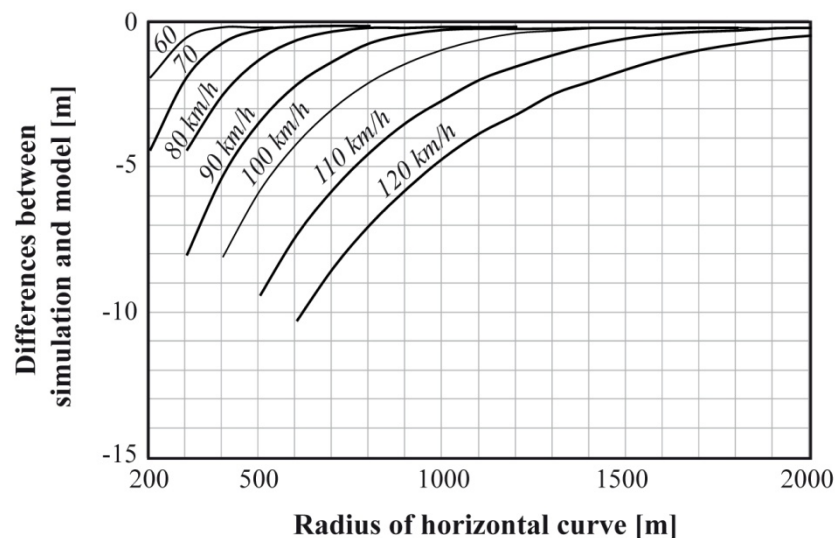


Figure 6: Differences in offset between simulation and the standard model.

In every case, the value derived from this study's methodology was lower than the value from Brazilian standards. In designs with small radii, the differences are maximized when they are also combined with high speeds. However, as the radius of the horizontal curve increased, the values for spacing from the simulation and from the model began to converge independently of design speed. It can be concluded that in restricted environments (small radii), a consideration of three-dimensionality, such as features of the cross-section in this case, becomes a significant element of project design. In the simulated scenario, the smallest observed difference in the radius of the horizontal curve was associated with low design speed

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($R = 600$ m; $V=60$ km/h), and the greatest difference occurred with high design speed ($V=120$ km/h) and a small radius of the horizontal curve ($R = 600$ m).

7 FINAL CONSIDERATIONS

Visibility conditions are derived from a combination of horizontal, vertical, and cross-sectional alignments, and therefore any changes in the road's geometry can modify visibility.

In the simulations, it was possible to analyze the problem (i.e., the position of barriers *versus* visibility) while considering the influence of various design elements. A comparison with the model for lateral offsetting fixed objects in horizontal curves, as given in Brazilian standards, showed that the lateral offset values found in the simulation were smaller than in the other model. An explanation for these differences is that the model provided by DNER (1999) and DER-SP (2006) is based on analyzing the situation two-dimensionally. In this model, the parameters that influence the positioning of objects in curves are restricted to the radius of the horizontal curve and the SSD. In this study, however, the geometric design and analyses were three-dimensional, and thus we could use features of spatial composition to position design elements more effectively. There are reservations with respect to reducing objects in curves. The case analyzed in the simulations is specific to longitudinal barriers with fixed dimensions, whereas the standardized model considers any type of object, including larger ones.

The offsets defined are recommended for barrier positions to guarantee SSD. Finally, to establish more consistent standards, it is suggested to future researches expand the set of assumptions and adopt more complex road projects that consider the impact of concave and convex vertical curves and changes in slope on visibility and barrier positioning in addition to defining a methodology for further validation of the results.

8 ACKNOWLEDGMENTS

The authors thank the Coordination for Improving Higher Education Personnel (CAPES–Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) by support student; the National Council for Scientific and Technological Development (CNPQ–Conselho Nacional de Desenvolvimento Científico e Tecnológico) for support this research under the Universal Project #470075/2010-4 and the author's productivity grants (PQ #300446/2010-1) and finally to FAPESP #2013/02379-7 by support the travel expenses.

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