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RELIABILITY OF STOPPING SIGHT DISTANCE DESIGN AT ROUNDABOUTS

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Abstract: The existing stopping sight distance (SSD) design method for roundabouts is deterministic. This means that all of the design variables are predetermined, fixed values. This study presents a probabilistic (Reliability-based) method for the determination of SSD at roundabouts based on an equation recommended by "A Policy on Geometric Design of Highways and Streets" (6th Edition), named as AASHTO Green Book, for calculation of SSD. The reliability based method considers all design variables (design speed, perception-reaction time, and vehicle deceleration rate) as random variables. In this method, correlation of random variables is taken into consideration. Three types of SSD (SSD for approaches, SSD along the circulatory roadway, and SSD for exiting vehicles to the pedestrian crosswalk) are considered in this study. The safety margin is defined as SSD provided by the roundabout geometry minus SSD required based on vehicle and driver performance characteristics. The First-Order Second-Moment (FOSM) and Advanced First-Order Second-Moment (AFOSM) methods were used to model SSD. Once the required SSD are determined, lateral clearance design values were determined based on probabilistic SSD and geometry of roundabouts. The reliability model developed in this study was applied to a roundabout and comparison is made between the results of FOSM, AFOSM, and deterministic methods. The reliability-based SSD design provides designers with the option to choose the level of reliability of their design.

1 INTRODUCTION

Safety is one of the dominant parameters for the design of roundabouts. In order for roundabouts to be safe, the SSD requirements must be met in every single point of roundabouts. Currently, SSD is calculated using formula recommended by AASHTO, in which the design variables are predetermined, fixed, values. The design variables in SSD calculation are vehicle speed, perception-reaction time, and vehicle deceleration rate. In reality, design variables are not fixed values, rather random variables which are sometimes correlated with one another. In Probabilistic approach, safety margin is defined as provided design element dimension minus required design element dimension. Although in transportation engineering, a negative value for the safety margin does not mean that an accident would happen, but it would impose some restrictions and increase the likelihood of occurrence of collisions (Easa and Hussain 2016).

The reliability-based design method is applied in different branches of civil engineering. Some authors have applied probabilistic method to the geometric design of highways such as horizontal curve design (Himes and Donnell 2014), Sight distance at railroad crossings (Easa 1994), Evaluation of sight distance for traffic safety (Santos-Berbel et al. 2017), Intersection sight distance (Easa 2000), Calibration of road design guidelines (Hussein et al. 2014), sight distance for turning vehicles on traffic signals (Hussain and Easa 2016), and reliability of lateral clearance (Sarhan and Hassan 2011). The reliability-based method is used by some authors for the design of traffic signals such as pedestrian signal timing on traffic signals (Easa and Cheng 2013) and Intergreen interval design at traffic signals (Easa 1993). The results of studies of the application of reliability-based design method in transportation engineering indicate that deterministic design method sometimes underestimates or overestimates the design values. For example, the result of study on left turn lanes offset distance indicates that deterministic design method overestimates left-turn lanes offset distance which would increase the overall cost of the project (Hussain and Easa 2016). The results of studies of the application of probability in transportation engineering indicate that reliability-based design values provide a more accurate representation of the requirements of design values based on the randomness of the design variables.

There are many reliability analysis methods including First-Order Second-Moment Method, the Point-Estimate Method, and Exact Method. Because of its ease of application, the First-Order Second-Moment (FOSM) method is widely used in different areas of science and engineering. FOSM method expands objective function about mean values of random variables (Easa 2000). Although the FOSM reliability method is easy to use, it has some shortcomings. These shortcomings include the lack of availability of information about distribution of variables, errors because of shortening of Taylor series, and that the reliability index depends on the way the objective function is defined, meaning, when the objective function is written in two different ways, two different reliability indexes are obtained. To overcome this error, Advanced First-Order Second-Moment (AFOSM) method uses the invariant reliability index. AFOSM is an iterative method which resolves the error associated with FOSM method. In this study, both FOSM and AFOSM methods are used to calculate SSD at roundabouts.

2 DETERMINISTIC METHOD

Stopping sight distance is defined as the distance a vehicle travels from the time driver sees an object to the time brakes are applied, plus the distance travelled by the vehicle from the time brakes are applied to the time vehicle comes to a complete stop (A Policy on Geometric Design of Highways and Streets, 2011). SSD is checked at three locations at roundabouts: approaches, the circulatory roadway, and the exits. For the approaches of roundabouts, SSD is provided at the pedestrian crosswalk and at the yield line. Figure 1 illustrates stopping sight distances and driver’s sightlines for each SSD for a single lane roundabout.

(Easa 2017) developed an analytical model for the determination of lateral clearance for symmetrical single-lane roundabouts. The author formulated lateral clearance for the roundabouts to satisfy SSD at the approaches, circulatory lane, and on the exits. SSD is considered to the pedestrian crosswalk and to the yield line for the approaches of roundabouts. Based on required SSD and the geometry of roundabouts, lateral clearance can be determined on every single point of the curves for the symmetrical single lane roundabout (Easa 2017).

Equation 1 is used for calculation of stopping sight distance at roundabouts (AASHTO 2011).

[1] $SSD = 0.278Vt + 0.039\frac{V^2}{a}$

where: V = vehicle speed (Km/h), t = perception-reaction time (s), and a = vehicle deceleration rate (m/s^2).

For calculation of stopping sight distance, a perception-reaction time (t) of 2.5 seconds and vehicle deceleration rate (a) of 3.4 m/s^2 is recommended (AASHTO 2011). For calculation of SSD using equation 1, design speed of the roundabout segment is considered as vehicle operating speed.

3 RELIABILITY-BASED METHOD

The First-Order Second-Moment and Advance First-Order Second-Moment methods are used to develop reliability-based models for the determination of SSD at roundabouts. Fundamentals of FOSM and AFOSM methods are briefly described, followed by the formulation of SSD with FOSM and AFOSM methods based on expression recommended by AASHTO.

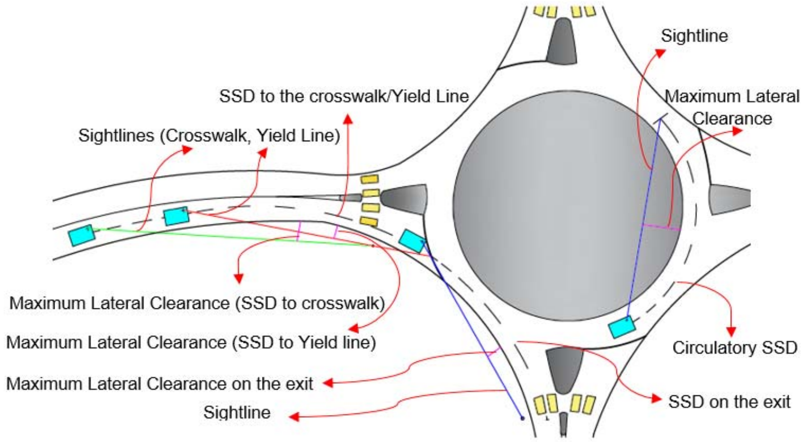

Figure 1: Stopping sight distances at roundabouts

3.1 First-Order Second-Moment (FOSM) Method

As the name of the First-Order Second-Moment (FOSM) implies, two moments (mean and variance) are required in the FOSM reliability method. The safety margin is expressed as:

[2] $F = f(X_{1,} X_{2,} X_{3,} \ldots\ldots, X_n)$

The Taylor series is used to expand and linearize the safety margin about the mean values of the variables ($\mu_{x1,} \mu_{x2,} \mu_{x3,} \ldots\ldots, \mu_{xn}$), and is expressed as:

[3] $F = f(\mu_{x1,} \mu_{x2,} \mu_{x3,} \ldots\ldots, \mu_{xn}) + \sum_{i=1}^{n} \frac{df(x_i)}{dX_i}(X_i - \mu_{xi}) + \frac{1}{2}\Sigma\Sigma \frac{\partial_f^2}{\partial X_i \partial X_j}(X_i - \mu_{xi})(X_i - \mu_{xj}) + \cdots$

In equation 3, the partial derivatives are calculated about the mean values of variables. The shortened form of Taylor series expansion is used to measure the approximate values of the mean and variance of the safety margin. The mean and variance of safety margin are expressed as:

[4] $E[F] \approx f(\mu_{x1,} \mu_{x2,} \mu_{x3,} \ldots\ldots, \mu_{xn})$

[5] $Var[F] = \sigma_F^2 = \Sigma\Sigma \frac{df(X_i)^2}{\partial X_i \partial X_j} Cov[x_i, x_j] + \sum_{i=1}^{n}(\frac{df(X_i)}{dX_i}\sigma_{xi})^2$

The partial derivatives in equation 5 are calculated using mean values and $Cov[x_i, x_j]$ is the covariance of x_i and x_j. Covariance describes how two variables are varying together. The covariance of x_i and x_j is expressed as:

[6] $Cov[x_i, x_j] = \rho_{x_i x_j}\sigma_{xi}\sigma_{xj}$

where: $\rho_{x_i x_j}$ = coefficient of correlation between x_i and x_j, σ_{xi} = standard deviation of random variable x_i, and σ_{xj} = standard deviation of random variable x_j.The coefficient of variation, CV, helps to illustrate how one random variable is dispersed compared to the mean of all other variables. The coefficient of variation (CV) is expressed as:

[7] $CV = \frac{\sigma_{xi}}{\mu_{xi}}$

where: σ_{xi} = standard deviation and μ_{xi} = mean value of variable x_i.Now, SSD at roundabouts is modeled with FOSM method based on formula recommended by (AASHTO 2011). Equation 1 is used for calculation of SSD at roundabouts. The design variables are denoted as (X) variables for ease of performance of mathematical operations and the required SSD, S_{Req}, is expressed as:

[8] $S_{Req} = 0.278X_1X_2 + 0.039\frac{X_1^2}{X_3}$

where: S_{Req} = required stopping sight distance (m), X_1 = vehicle speed (Km/h), X_2 = perception-reaction time (s), and X_3 = deceleration rate (m/s^2).

The safety margin (F) for SSD at Roundabouts is defined as SSD provided by the geometry of roundabouts minus SSD required based on vehicle and driver characteristics. Since the design elements in probability method are random variables, safety margin (F) is also a random variable. The safety margin is expressed as:

[9] $F = S_{sup} - S_{Req}$

where: S_{sup} = supplied SSD and S_{Req} = required SSD. The expected value of required SSD, $\mathrm{E}[S_{Req}]$, is given:

[10] $\mathrm{E}[S_{Req}] = 0.278\mu_{x1}\,\mu_{x2} + 0.039\frac{\mu_{x1}^{2}}{\mu_{x3}}$

where: μ_{x1} = mean value of vehicle speed ($\mathrm{Km/h}$), μ_{x2} = mean value of perception-reaction time (s), and μ_{x3} = mean value of vehicle deceleration rate ($\mathrm{m/s^2}$).

The mean and variance of safety margin (F) are given by equations 11 and 12, respectively.

[11] $E[\mathrm{F}] \approx S_{supply} - \mathrm{E}[S_{Req}]$

[12] $Var[F] = \sigma_F^2 = 2\frac{df(X)}{dX_1}\frac{df(X)}{dX_2}Cov(X_1, X_2) + 2\frac{df(X)}{dX_1}\frac{df(X)}{dX_3}Cov(X_1, X_3) + (\frac{df(X)}{dX_1}\sigma_{x1})^2 + \left(\frac{df(X)}{dX_2}\sigma_{x2}\right)^2 + (\frac{df(X)}{dX_3}\sigma_{x3})^2$

The derivatives of safety margin are given as:

[13] $\frac{df(X)}{dX_1} = 0.278X_2 + 0.078\frac{X_1}{X_3}$

[14] $\frac{df(X)}{dX_2} = 0.278X_1$

[15] $\frac{df(X)}{dX_3} = -\frac{0.039X_1^2}{{X_3}^2}$

The safety of proposed design can be expressed in term of reliability index (β). Reliability index is expressed as:

[16] $\beta = \frac{\mathrm{E}\,[\mathrm{F}]}{\sigma_\mathrm{F}}$

where: $\mathrm{E}[\mathrm{F}]$ and σ_F are given by Equations 4 and 5 (note that $\sigma_\mathrm{F} = \sqrt{Var[\mathrm{F}]}$).

The probability of failure is expressed as:

[17] $\mathrm{P_f} = \Phi(-\beta) = 1 - \Phi(\beta)$

where: $\Phi(-\beta)$ = sum of the area under the density curve of the safety margin from -∞ to $-\beta$. The table of standard normal variate or computer software's are used to obtain the value of $\Phi(-\beta)$. Based on assigned probability of failure (P_f), the corresponding value of β is used for the calculation of SSD at roundabouts.

Substituting value of E(F) from equation 16 to equation 11 and calculating for provided SSD (S_{prov}) will yield the following equation:

[18] $S_{sup} = \beta\sigma_F + E(S_{req})$

3.2 Advanced First-Order Second-Moment (AFOSM) Method

The advanced First-Order Second-Moment reliability method is developed by (Hasofer & Lind 1974). According to the author, the point chosen from failure boundary for linear approximation will provide the invariant reliability index. The safety margin (F) is already defined in equation 2. Generally, it is more favorable to work in terms of normalized variables. Normalized or standardized variables are dimensionless. The normalized variable (y_i) is given by:

[19] $y_i = \frac{x_i - \mu_{xi}}{\sigma_{xi}}$

where: σ_{xi} = standard deviation, μ_{xi} = mean value, and x_i = obtained value of a variable.

The mean value of normalized variable y_i is zero and its standard deviation is one. The safety margin is evolved with standardized variables, $y_1, y_2, y_3, \ldots\ldots, y_n$, and expressed as:

[20] $Z = h(y) = h(y_1, y_2, y_3, \ldots\ldots, y_n)$

The Taylor series, first-order approximation of Z, at the standard design values at which the approximation is taken, $y_i^* = h(y_1^*, y_2^*, y_3^*, \ldots\ldots, y_n^*)$, is expressed as:

[21] $Z = \sum_{i=1}^{n}(y_i - y_i^*)\, dh(y^*)/d(y_i^*)$

where: $dh(y^*)/d(y_i^*)$ = first derivatives of performance function with respect to y_i, calculated at design points, y_i^*. The mean, μ_z and standard deviation, σ_z, of Z are given by:

[22] $\mu_z = -\frac{\sum_{i=1}^{n}(y_i^*)dh(y^*)}{d(y_i^*)}$

[23] $\sigma_z = \sqrt{\sum_{i=1}^{n} dh(y^*)/d(y_i^*)^2}$

The solution in terms of normalized variables is given by:

[24] $y_i^* = -\frac{\frac{dh(y^*)}{d(y_i^*)}}{\sigma_z}(\beta + \frac{h(y)}{\sigma_z})$

where: σ_z = standard deviation, β = reliability index, and $h(y)$ = performance function.

The distance from the origin to y^*, which is the minimum distance, is the reliability index, β. The reliability index (β) is expressed as:

[25] $\beta = \sqrt{\sum_{i=1}^{n} y_i^2}$

The iterative algorithm for determination of reliability index (β) can be find on (Smith 1986).

When random variables, $X_1, X_2, X_3, \ldots\ldots, X_n$, are correlated with each other, a procedure is used to transform the correlated variables to noncorrelated variables, while allowing for correlation effects. After safety margin is evolved with transformed, uncorrelated, and reduced variables, the AFOSM procedure, described early, will be applied. The covariance matrix, denoted as CV_X, for correlated variables, $X_{1,} X_{2,} X_{3,} \dots\dots, X_n$, is expressed as:

$$[26]\ CV_X = \begin{bmatrix} \sigma_{x1}^2 & \cdots & COV(X_1, X_n) \\ \vdots & \ddots & \vdots \\ COV(X_n, X_1) & \cdots & \sigma_{xn}^2 \end{bmatrix}$$

The leading diagonal values of the covariance matrix, CV_X, are variances of the correlated variables and the off-diagonal values are the related covariances. The covariance matrix is used to find uncorrelated variables. Procedure for determination of uncorrelated variables is basically determination of eigenvalues and eigenvector of covariance matrix. The eigenvalue and eigenvector of covariance matrix can be obtained using Jacobi's method. The eigenvalues are variance of transformed variables and original variables, $X_{1,} X_{2,} X_{3,} \dots\dots, X_n$, multiplied by eigenvector will give the values of a set of transformed and uncorrelated random variables, $Y_{1,} Y_{2,} Y_{3,} \dots\dots, Y_n$. To obtain a set of reduced and uncorrelated variables, the uncorrelated variables, $Y_{1,} Y_{2,} Y_{3,} \dots\dots, Y_n$, are standardized. Once the reduced, uncorrelated variables, $y_{1,} y_{2,} y_{3,} \dots\dots, y_n$, are determined, $X_{1,} X_{2,} X_{3,} \dots\dots, X_n$ are calculated in terms of $y_{1,} y_{2,} y_{3,} \dots\dots, y_n$ and substituted into safety margin. Once the safety margin is expressed with transformed, reduced, and uncorrelated variables, the AFOSM method can be applied.

The safety margin (F) for the system is defined in equation 9. Before applying the AFOSM method to equation 9, the correlated variables need to be transformed into noncorrelated variables while allowing for the correlation effects. After the safety margin is evolved with transformed, uncorrelated, and reduced variables, $y_1, y_{2,} y_3$, the AFOSM method is applied. The iterative algorithm is applied for the determination of the invariant reliability index (Smith, 1986).

4 Design Values

Tables 1 and 2 present the lateral clearance design values for the approaches of roundabouts to satisfy SSD calculated with FOSM method to the crosswalk and the yield line, respectively. Tables 3 and 4 presents the lateral clearance design values for the approaches of roundabouts to satisfy SSD calculated with AFOSM method to the crosswalk and the yield line, respectively. The SSD used to calculate maximum lateral clearances for tables 1, 2, 3, and 4 are based on system probability of failure of 0.01% and coefficient of variation of 10% for all random variables.

Table 1: Design values of lateral clearance on the approaches (SSD to the crosswalk), FOSM Method

First Entry Curve Radius	Second Entry Curve Radius	Maximum Lateral Clearance (m)			
		Speed (Km/h) *			
		40	50	60	70
		Stopping Sight Distance (m)			
R_1 (m)	R_2 (m)	48	65	85	109
100	20	4.7	6.9		
	30	4.3	6.6		
	40	4.2	6.5		
500	20	3.3	3.6	3.9	4.8
	30	2.9	3.1	3.5	4.4
	40	2.6	2.9	3.2	4.2
1000	20	3.2	3.4	3.6	3.8
	30	2.8	3.0	3.1	3.3
	40	2.5	2.7	2.9	3.0

*For shaded cells, R_1 is less than R_{min} for the respective vehicle speed on the approaches and the superelevation of up to 0.06.

Table 2: Design values of lateral clearance on the approaches (SSD to Yield Line), FOSM Method

Entry Curve Radius	Entry Curve Radius	Maximum Lateral Clearance (m)			
		Speed (Km/h) *			
		40	50	60	70
		Stopping Sight Distance (m),			
R_1 (m)	R_2 (m)	48	65	85	109
100	20	4.3	6.5		
	30	3.0	5.4		
	40	2.4	4.8		
500	20	3.1	3.7	4.3	5.1
	30	1.6	2.1	2.6	3.7
	40	0.8	1.3	1.9	3.0
1000	20	2.9	3.4	3.9	4.3
	30	1.4	1.8	2.2	2.5
	40	0.7	1.0	1.3	1.7

*For shaded cells, R_1 is less than R_{min} for the respective vehicle speed on the approaches and the superelevation of up to 0.06.

Table 3: Design values of lateral clearance on the approaches (SSD to the crosswalk), AFOSM Method

First Entry Curve Radius	Second Entry Curve Radius	Maximum Lateral Clearance (m)			
		Speed (Km/h) *			
		40	50	60	70
		Stopping Sight Distance (m),			
R_1 (m)	R_2 (m)	51	70	95	130
100	20	5.0	7.6		
	30	4.7	7.4		
	40	4.5	7.3		
500	20	3.4	3.6	4.2	5.9
	30	3.0	3.2	3.8	5.5
	40	2.7	2.9	3.6	5.4
1000	20	3.2	3.5	3.7	4.1
	30	2.8	3.0	3.2	3.7
	40	2.5	2.7	3.0	3.5

*For shaded cells, R_1 is less than R_{min} for the respective vehicle speed on the approaches and the superelevation of up to 0.06.

The SSD calculated with AFOSM method is larger compared to FOSM method for the same probability of failure. The reason that FOSM method provides lower design value is that AFOSM removes the error associated with the FOSM reliability method. Since the AFOSM SSD design values are larger than FOSM SSD, the lateral clearance design values to satisfy AFOSM SSD is larger than lateral clearance values to satisfy FOSM SSD. The lateral clearance design values obtained to satisfy FOSM and AFOSM SSD are nearly equal when entry radii, R_1, R_2, are large and approach design speed is low and vice versa.

Table 4: Design values of lateral clearance for AFOSM, SSD on the approaches (SSD to Yield Line)

First Entry Curve Radius	Second Entry Curve Radius	Maximum Lateral Clearance (m)			
		Speed (Km/h) *			
		40	50	60	70
		Stopping Sight Distance (m),			
R_1 (m)	R_2 (m)	51	70	95	130
100	20	4.7	7.3		
	30	3.4	6.2		
	40	2.8	5.6		
500	20	3.2	3.9	4.6	6.1
	30	1.7	2.3	3.0	4.8
	40	0.9	1.4	2.3	4.2
1000	20	3.0	3.6	4.0	4.6
	30	1.5	1.9	2.3	2.9
	40	0.8	1.1	1.4	2.2

*For shaded cells, R_1 is less than R_{min} for the respective vehicle speed on the approaches and the superelevation of up to 0.06.

5 APPLICATION

The application involved the use of a symmetrical single-lane roundabout with two entry curves, curved in the same direction. The radius of first entry curve (R1) was 200 m and the radius of the second entry curve (R2) was 40 m. Figure 2 illustrates the geometry of roundabouts on the approach. The approach SSD was calculated based on probability of failure (P_f) of 0.01%. The reliability index (β) corresponding to $P_f = 0.01\%$ is 3.72. Since the mean values of design variables are required, mean values were calculated from the extreme values with the assumption that random variables are normally distributed. The expression relating mean and extreme value is given by:

[27] $\mu_X = \frac{X}{1+Z\ CV}$

where: X = extreme value, μ_X = mean value, CV = coefficient of variation, and Z = number of standard deviations of the normal distribution corresponding to a certain percentile. In this example, perception-reaction time is assumed to represents 95th percentile (Z=1.65), vehicle deceleration rate is assumed to represents 5th percentile (Z=-1.65), and vehicle speed is assumed to indicate 99th percentile speed (Z=2.32). The data used in reliability analysis, in both FOSM and AFOSM methods, are illustrated in table 5.

Table 5: Data used for probabilistic approach SSD design*

Variables	Extreme Value	Mean Value	Coefficient of Variation (%)
V (Km/h)	60	48.7	10
t (s)	2.5	2.15	10
a (m/s^2)	3.4	4.07	10

* $\rho_{x_1x_2} = +0.5 \quad \rho_{x_1x_3} = -0.5$

Based on design speed of 60 km/h and extreme values recommended for perception-reaction time (t = 2.5 s) and vehicle deceleration rate (a = 3.4 m/s^2), the required SSD is 83 meters (AASHTO, 2011).

When the FOSM method is applied, E(S_{req}) and σ_F were calculated as 51.83 and 9.28 using equations 10 and 12, respectively (note that $\sigma_F = \sqrt{Var[F]}$). Using the equation 18, the required (supplied) SSD was calculated as 86 meters.

The iterative algorithm presented in (Smith 1986) was used to produce stable reliability index. The required SSD was calculated with AFOSM method by trial as 95 meters. The calculated design parameters corresponding to the final iteration is illustrated in table 6.

Maximum lateral clearance to satisfy deterministic SSD was calculated as 5.5 m for to the pedestrian crosswalk and 4 m to the yield line, respectively. Maximum lateral clearance to satisfy FOSM SSD was calculated as 5.8 m to the crosswalk and 4.3 m to the yield line, respectively. Maximum lateral clearance to satisfy AFOSM SSD was 6.8 m to the crosswalk and 5.3 m to the yield line, respectively. Table 7 presents the results of the design elements calculated with the deterministic, FOSM, and AFOSM methods.

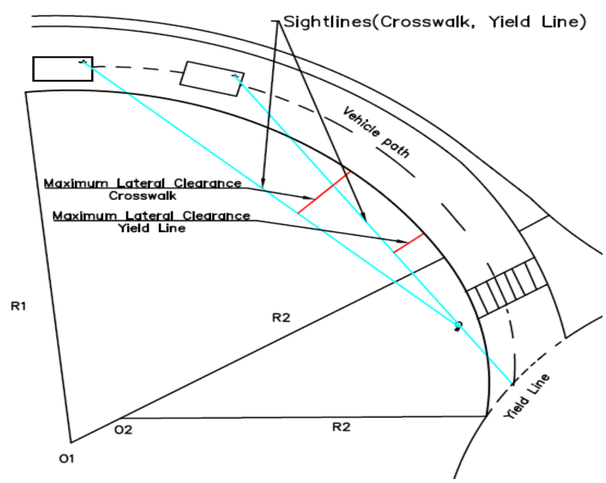

Figure 2: Stopping Sight Distance on the approach to the crosswalk

Table 6: Design parameters related to final iteration

Variables	y_i^*	X_i^*
V	0.77	65.70
T	1.05	2.08
a	-3.48	2.96

Table 7: Comparison of the results for design elements

Design Methods	Stopping Sight Distance (m)	Maximum Lateral Clearance (m) (SSD to crosswalk)	Maximum Lateral Clearance (m) (SSD to Yield line)
Deterministic	83	5.5	4.0
FOSM	86	5.8	4.3
AFOSM	95	6.8	5.3

The SSD design values of deterministic method was 3.5% lower than the SSD design value of the FOSM method and 12% lower than the SSD design value of the AFOSM method. The SSD calculated with AFOSM method was 9% larger than the SSD calculated with the FOSM method. The lateral clearance design value to satisfy deterministic SSD was 5% lower than the lateral clearance value to satisfy the FOSM SSD. Since the AFOSM provided larger SSD design value compared to the FOSM and deterministic methods, the lateral clearance value to satisfy AFOSM SSD was 19% larger than the lateral clearance value to satisfy deterministic SSD and 15% larger than lateral clearance value to satisfy FOSM SSD value.

6 CONCLUSION

The current method of calculating the SSD for roundabouts is deterministic (all of the design variables are predetermined, fixed values). The reliability-based design of SSD at roundabouts uses random variables as design variables. One of the major parameters in the design of SSD, in reliability-based design method, is accuracy of design variables. Since the random variables considered in the probabilistic methods vary, it is recommended that the vehicles operating speed, drivers perception-reaction time, and vehicles deceleration rate are measured on the field for the specific roundabout under study and the variability of these variables are used in the design.

A high level of reliability required larger SSD and vice versa. The literature suggests that the probability of failure for facilities are chosen based on the level of importance of the facilities. One of the major benefits of the probabilistic design method is that it provides designers insight into the reliability of their design. The SSD design value calculated with probabilistic method provide more precise lateral clearance design value based on the randomness of the design variables. The probability methods developed in this study would be useful for designers to select SSD design values based on their desired probability of failures. Design aids were developed for the lateral clearance requirements on the approaches to satisfy SSD. The largest of the lateral clearances design values obtained to satisfy SSD to the crosswalk and to the yield line should be provided for the entire length of the entry curves.

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