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DESIGN OF OVERTAKING SIGHT DISTANCE IN HIGHWAYS USING PROBABILISTIC APPROACH

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Abstract: The design of Overtaking Sight Distance (OSD) is an important aspect of highway geometrics. The current procedure of OSD design is based on deterministic methodology. Literatures available report that significant variability is associated with input parameters for OSD design. The present study deals with the characterisation of OSD variability considering different cases of input parameter variability. The Monte Carlo Simulation (MCS) technique has been adopted to derive the distributions of OSD, which are also statistically established by Chi-square Goodness of Fit (GOF) test. In all the cases, OSD is found to follow lognormal distribution. The Coefficient of Variation (COV) of OSD is found to vary from 21.45% to 22.91% and 23.66% to 25.66% for one-way traffic and two-way traffic condition respectively. Thus, the variability associated with OSD appears to be significant and necessitates probabilistic approach in OSD design. A simple design methodology has been presented for reliability based OSD design taking input parameter variability into account.

Keywords: Overtaking Sight Distance (OSD); Variability; Monte Carlo Simulation (MCS); Reliability; Goodness of Fit (GOF)

1. Introduction:

Geometric design of highways constitutes an aspect of paramount importance for maintaining speed without compromising safety. One of the most important considerations to be made in highway geometric design is that of providing adequate sight distance. The highway should be designed for providing adequate sight distance to the driver all along the route so that visibility is never a constraint and speed can be maintained throughout. In order to address the safety issue by visibility criteria, the two basic types of sight distances for which the highway is to be designed are Stopping Sight Distance (SSD) and Overtaking Sight Distance (OSD). SSD is the minimum distance required by the vehicle moving at the design speed to stop in case an obstruction is encountered and is, therefore, indispensable to be provided throughout the entire length of the highway for safety. On the other hand, OSD is the minimum distance visible ahead which is to be provided to enable the driver of vehicle moving at design speed overtakes the slow moving vehicles. For efficient movement of traffic in high priority road networks like Expressways, National Highways and State Highways, provision of this facility for overtaking is mandatory for attaining high Level of Service (LOS) and thus, it is equally important to design the highway for OSD. The current procedure for OSD design recommended by various guidelines is based on deterministic approach [1-4]. The input parameters which are used for OSD design include speed of the overtaking and overtaken vehicle, driver reaction time and acceleration of overtaking vehicle. It is noteworthy that various researchers have reported that these input parameters like vehicular speed, reaction time of driver and acceleration of overtaking vehicle exhibit significant variability in practical scenario [5-10]. As such, there appears to be a need to incorporate probabilistic approach in the design of OSD. This is what forms the scope of the present work. The issue of SSD design by probabilistic approach has been investigated by various researchers and may be seen elsewhere [11-15]. However, the significance of probabilistic approach incorporation in OSD design largely remains unexplored and therefore, has been taken up for the present study.

2. Objective of Study:

The objectives of the present study are:

i. To study and characterize the variability of OSD considering various combinations of probability distributions for input parameters for both one-way and two-way traffic.

ii. To establish the level of acceptability of probability distributions used for characterizing the variability of OSD based on Goodness of Fit (GOF) test.
iii. To develop a design methodology for OSD design by probabilistic method and calibrate OSD required for achieving various reliability levels.
iv. To prepare a design chart by means of which designer can adopt probabilistic approach for reliability based OSD design and also, understand the safety consequences of his decision.

3. Background and Literature Review:

The principles of reliability or probabilistic approach in the context of sight distance considerations have been studied by several researchers. A probabilistic model was adopted by Faghri and Demetsky[16] to study the probability of collision due to limitation in sight distance at road-railway grade crossings. Navin [17] discussed the issues of reliability based design of typical highway elements. Probabilistic approach for sight distance at intersections was studied by Easa[11]. Robust simulation techniques like Monte Carlo Simulation (MCS) was used by other researchers to estimate sight distance limitations on straight highway segments and in the design of horizontal curves overlapping with flat gradient, crest curve and sag curves [12, 18]. Ismail and Sayed [19] developed a methodology for calibrating standard design models for design safety level. Measures of design reliability and expected collision frequency were linked by applying a reliability based quantitative risk measure in the study by Ismail and Sayed [20]. Hussein et al [15] presented an application of reliability analysis for the calibration of geometric design models to yield consistent and adequate safety levels. Llorca et al. [10] developed a reliability analysis on overtaking sight distance, based on observation of manoeuvres in a sample of Spanish two-lane roads.

Concept of Reliability: Reliability (R) can be defined as the probability (P) that an undesired event exceeds a certain threshold. In the present study, reliability is the probability that the required overtaking sight distance (ROSD) is less than the available overtaking sight distance (AOSD) for ensuring safety.

$$R = P(ROSD < AOSD) \qquad (1)$$

Thus, the probability of failure (P_f) is given by**,**

$$P_f = 1 - R \qquad (2)$$

P_f can also be referred to as the probability of risk, as shown in Figure 1.

Overtaking Sight Distance (OSD): OSD is the minimum distance open to the vision of the driver of a vehicle intending to overtake slow vehicle ahead with safety and that may or may not be against the traffic of opposite direction considering two-way and one-way traffic respectively. As shown in Figure 2, where A, B and C are overtaking, overtaken and vehicle coming from opposite direction, OSD (in metre) can be calculated as [3, 4],

$$OSD = d_1 + d_2 + d_3 \qquad (3)$$

Where,

$$d_1 = 0.28 V_b t$$

$$d_2 = 2s + 0.28 V_b T$$

$$d_3 = 0.28 VT$$

V_b= Speed of overtaken (slow moving) vehicle in km/hr = (V-16),
t = Reaction time in sec,
V = Speed of overtaking vehicle in km/hr,

$T = \sqrt{4s/a}$, Time taken for the actual overtaking operation in sec

s = Spacing of vehicles (m) = ($0.2V_b$+6)
a = Acceleration of vehicle in m/s^2

In Figure 2, t_0, t_1 and t_2 represent the instants of time during the course of overtaking operation.
In case of divided highways having one-way traffic in all the lanes, OSD is given by,

$$OSD = d_1 + d_2 \qquad (4)$$

Variability of Input Parameters: Review of literature for studying the uncertainty associated with the input parameters of OSD design presents the following details by previous researchers:

Vehicular speed: Richl and Sayed [8] reported that the speed with which vehicles move varies with road element and driver behaviour. The operating speed of vehicles can be considered to be normally distributed [7]. The distribution parameters of speed distribution were studied by Richl and Sayed [21].
Reaction time: Previous studies conducted to determine the distribution of driver perception and reaction time reported it to be lognormally distributed [5, 22]. The reaction time of driver varies depending on age, emotional, intellectual and other human characteristics.

Acceleration of overtaking vehicle: The variability in acceleration of overtaking vehicles was established as lognormal distribution in the study by Llorca et. al. [10]. The types of vehicle overtaking and driver characteristics besides other environmental factors mainly contribute to variability in acceleration values for different vehicles in highways.

3. Results and Discussions:

In the present study, the variability of OSD is simulated adopting three cases of input parameters' distributions. The distributions and distribution parameters of input parameters for OSD design are adopted based on literature review and are shown in Table 1. The Monte Carlo Simulation (MCS) technique has been adopted to simulate the variability of OSD for all the three cases and considering both one-way and two-way traffic conditions
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OSD variability for one-way traffic: In case of one-way traffic condition prevailing in divided highways of more than 2 lanes such as Expressways and National Highways, the requirement of OSD can be computed using Equation 4. Therefore, MCS is performed over Equation 4 to simulate the variability of OSD considering the input parameters variability as per Case I for 10, 000 data points and the output histogram of OSD is derived. The output histogram of OSD is fitted with both normal and lognormal distributions using Maximum Likelihood method. This is shown in Figure 2. In order to determine the best distribution for OSD and its level of acceptability, the Chi-square Goodness of Fit (GOF) test is performed at 95% confidence level. It is found that the distribution of OSD fails Chi-square GOF test for both normal and lognormal distribution at 10,000 data points. Olivares and Forero [23] reported that large sample size may lead to rejection of null hypothesis, yet the model may be acceptable. As such, MCS is performed again considering lesser sample size at 95% confidence level to establish the best possible distribution for OSD. It is found that the lognormal distribution for OSD passes Chi-square GOF test at 1,000 data points and the results are shown in Table 2. Thus, in Case I, statistically it is established that OSD is lognormally distributed with Coefficient of Variation (COV) of 22.91%. Adopting similar procedure, the input parameters are taken as per Case II and Case III of Table 1 and MCS is performed to derive the distribution of OSD at 95% confidence level. The Chi-square GOF test establishes that OSD follows lognormal distribution for Case II and Case III with COVs of 21.45% and 21.95% respectively at 95% confidence level considering 1,000 data points. The results of Chi-square GOF test for Case II and Case III are shown in Table 3 and 4 respectively.

OSD variability for two-way traffic: In a developing country like India, a number of National and State Highways still consist of undivided 2 lanes only. Under such circumstances, the requirement of OSD is calculated as per Equation 3. In order to derive the distribution of OSD considering two-way traffic, MCS is performed over Equation 3 with each of the input parameter distribution as per Case I, II and III as per Table 1. The results of Chi-square GOF test conducted at 95% confidence level establishes lognormal distribution for OSD in all the Cases I, II and III for two-way traffic at 1,000 data points and are shown in Tables 5, 6 and 7 respectively . The COVs of OSD in Case I, II and III are found to be 25.66%, 23.66 % and 23.68% respectively.

Thus, it is found that OSD follows lognormal distribution in all the possible Cases I, II and III considering both one-way and two-way traffic conditions. This is also established by performing Chi-square GOF test at 95% confidence level. For one-way traffic condition, the COV of OSD is found to vary from 21.45% to 22.91%. On the other hand, the COV of OSD varies from 23.66% to 25.66% for two-way traffic. Thus, it is observed that when the mean and standard deviation of input parameters are unchanged, the variation in COVs of OSD due to variation in distribution of input parameters is not appreciable in all the cases. It is, however, noteworthy that significant variability is associated with OSD determination and that the uncertainty of OSD is more in two-way traffic compared to one-way traffic condition. The reason for this can be attributed to the fact that in two-way traffic, additional input parameter uncertainty is introduced in the design Equation 3 in the form of speed of vehicle (V) coming from opposite direction. Therefore, it appears that the current deterministic procedure of OSD design may not be capable enough to accommodate input parameter uncertainty. As such, probabilistic method of OSD design needs to be incorporated in the design practice.

Design Methodology for Overtaking Sight Distance by Probabilistic Approach: A simple design methodology is presented for reliability based design of OSD. In this methodology, the designer needs to decide the level of reliability for which OSD is to be designed. With the derived distribution and distribution parameters of OSD derived in the earlier section, the designer can calculate the amount of OSD required for achieving that reliability level as shown in Equation 5,

$$OSD_{reqd.} = \exp((\ln \mu) + z_R \sigma) \text{ [24]} \quad (5)$$

Where,
μ = mean of OSD distribution
z_R= Standard normal deviate for probability or reliability (R), z_R value can be obtained from standard normal distribution table. $\sigma^2 = \ln(1+COV_{OSD}^2)$, Where COV = Coefficient of Variation of lognormal OSD.

This model of reliability based design was incorporated by Rajbongshi and Das [24] for estimation of structural reliability of asphalt pavement. In the present study, this probabilistic approach has been incorporated in the design of OSD. With the proposed methodology and using Equation 5, the requirement of OSD in terms of achieving various reliability levels has been calibrated for Case I of one-way traffic and two-way traffic. The results are shown in Table 8 and 9. With the results shown in Table 8, design chart has been prepared for OSD required and reliability level for Case I of one-way traffic condition. Thus, following the same procedure, the OSD requirement for various reliability levels can be calibrated and design charts can be prepared considering all the possible Cases I, II and III of one-way and two-way traffic condition. The design charts, thus, developed are shown in Figures 5 to 10. The design charts can serve as useful tools for designers to design OSD for desired level of reliability by probabilistic approach. For instance, if a designer wants to design OSD for achieving 90% reliability in two-way traffic with distribution as per Case I, he can refer to Figure 8 and directly determine the amount of OSD to be provided in the field. Also, the designer can understand the safety consequences of his decision of providing different OSD in field by referring to the design charts.

Table 1: Variability of Input parameters considered in the simulation study for Overtaking Sight Distance.

Parameter	Mean	Std. Deviation	Distribution		
			Case I	Case II	Case III
Speed of overtaking vehicle	90 km/hr	4.81 km/hr	Normal	Lognormal	Lognormal
Reaction time of driver	2.5 s	0.67 s	Normal	Normal	Lognormal
Acceleration of overtaking vehicle	0.77 m/s^2	0.47 m/s^2	Lognormal	Lognormal	Lognormal

Table 2: Results of Chi-square test for normal and lognormal distribution of Overtaking Sight Distance for one-way traffic (Case I).

Parameter	Normal	Lognormal
Mean (m)	336.52	336.43
Std. Deviation (m)	78.52	77.06
Null Hypothesis	Fail	Pass
Probability of acceptance	9.44×10^{-10}	0.75
Chi-square statistic	44.96	1.94
COV (%)	23.33	22.91

Table 3: Results of Chi-square test for normal and lognormal distribution of Overtaking Sight Distance for one-way traffic (Case II).

Parameter	Normal	Lognormal
Mean (m)	335.35	335.33
Std. Deviation (m)	72.32	71.91
Null Hypothesis	Fail	Pass
Probability of acceptance	1.99×10^{-9}	0.79
Chi-square statistic	46.45	2.42
COV (%)	21.57	21.45

Table 4: Results of Chi-square test for normal and lognormal distribution of Overtaking Sight Distance for one-way traffic (Case III).

Parameter	Normal	Lognormal
Mean (m)	315.26	315.22
Std. Deviation (m)	69.92	69.20
Null Hypothesis	Fail	Pass
Probability of acceptance	2.09×10^{-9}	0.51
Chi-square statistic	46.35	4.27
COV (%)	22.18	21.95

Table 5: Results of Chi-square test for normal and lognormal distribution of Overtaking Sight Distance for two-way traffic (Case I).

Parameter	Normal	Lognormal
Mean (m)	624.30	623.94
Std. Deviation (m)	165.31	160.12
Null Hypothesis	Fail	Pass
Probability of acceptance	1.67×10^{-14}	0.19
Chi-square statistic	67.23	6.16
COV (%)	26.48	25.66

Table 6: Results of Chi-square test for normal and lognormal distribution of Overtaking Sight Distance for two-way traffic (Case II).

Parameter	Normal	Lognormal
Mean (m)	628.08	627.91
Std. Deviation (m)	150.92	148.55
Null Hypothesis	Fail	Pass
Probability of acceptance	1.44×10^{-15}	0.15
Chi-square statistic	78.89	9.51
COV (%)	24.03	23.66

Table 7: Results of Chi-square test for normal and lognormal distribution of Overtaking Sight Distance for two-way traffic (Case III).

Parameter	Normal	Lognormal
Mean (m)	604.97	605.08
Std. Deviation (m)	141.78	143.25
Null Hypothesis	Fail	Pass
Probability of acceptance	1.12×10^{-11}	0.17
Chi-square statistic	62.96	10.32
COV (%)	23.44	23.68

Table 8: Calibration of OSD against various reliability levels for one-way traffic (Case I).

Reliability	OSD required
50	336.43
60	356.25
70	378.77
80	407.02
90	449.61
95	488.09
99	569.89

Table 9: Calibration of OSD against various reliability levels for two-way traffic (Case I).

Reliability	OSD required
50	623.94
60	665.09
70	712.20
80	771.74
90	862.43
95	945.21
99	1123.69

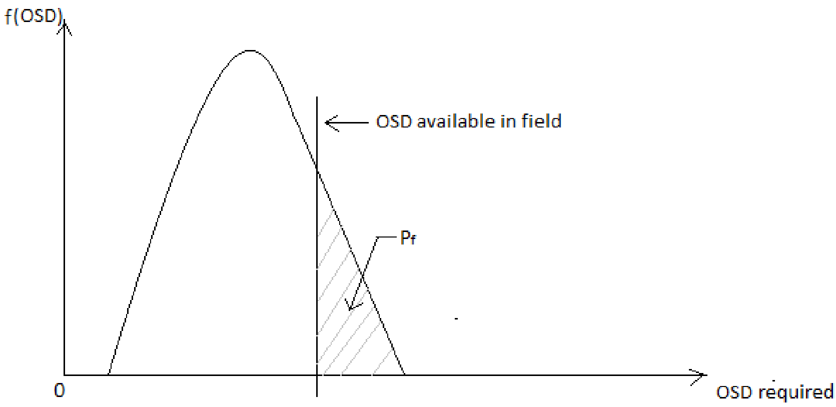

Figure 1: Schematic plot of probability distribution of Overtaking Sight Distance (OSD).

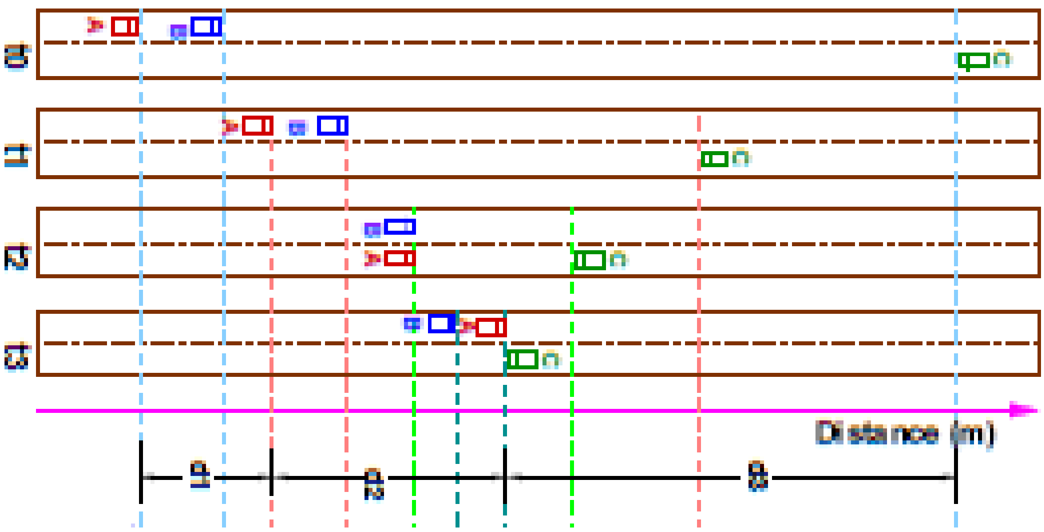

Figure 2: Estimation of Overtaking Sight Distance (Source:NPTEL[25] 2006).

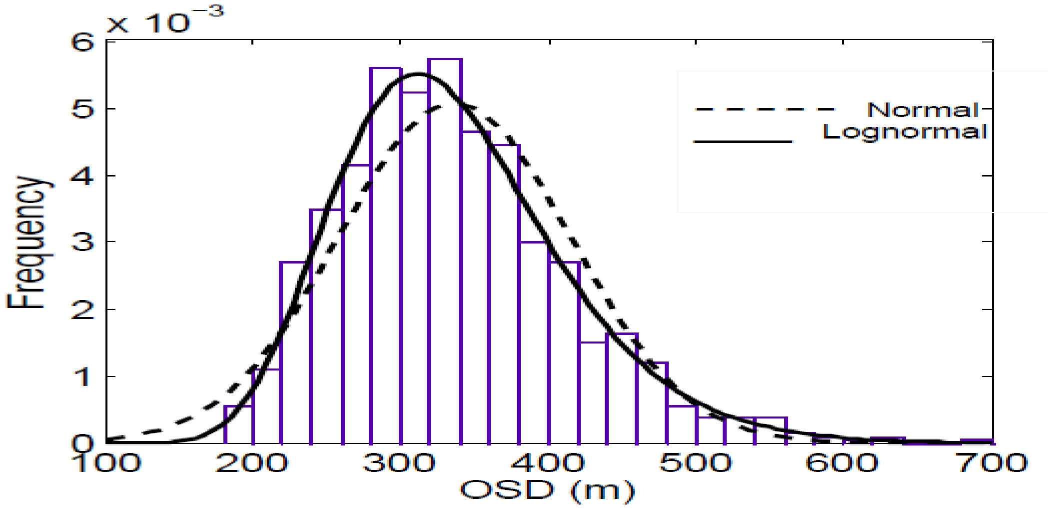

Figure 3: Frequency distribution of OSD (Case I) for one-way traffic.

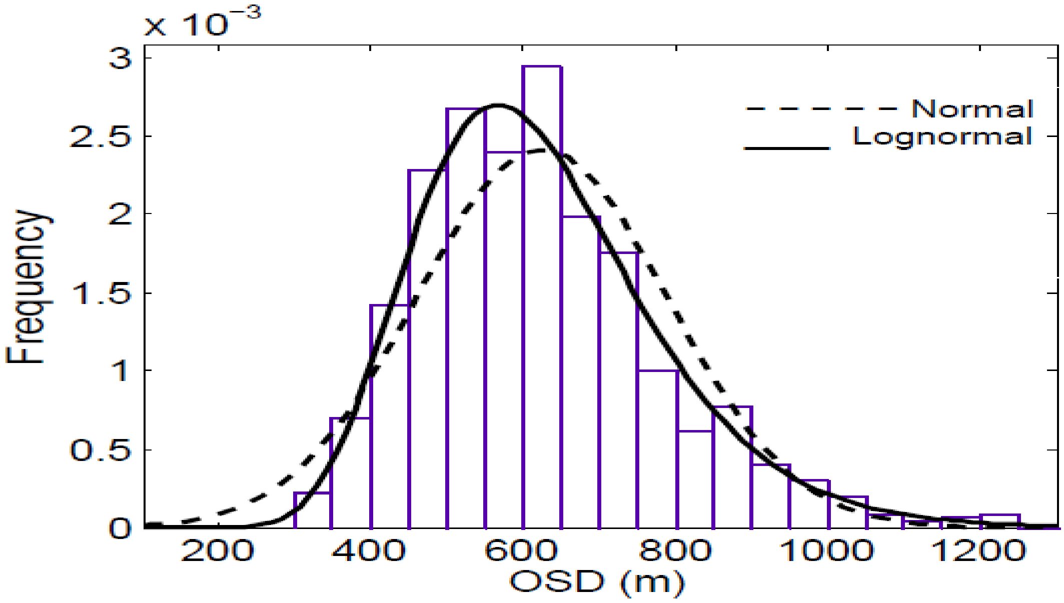

Figure 4: Frequency distribution of OSD (Case I) for two-way traffic.

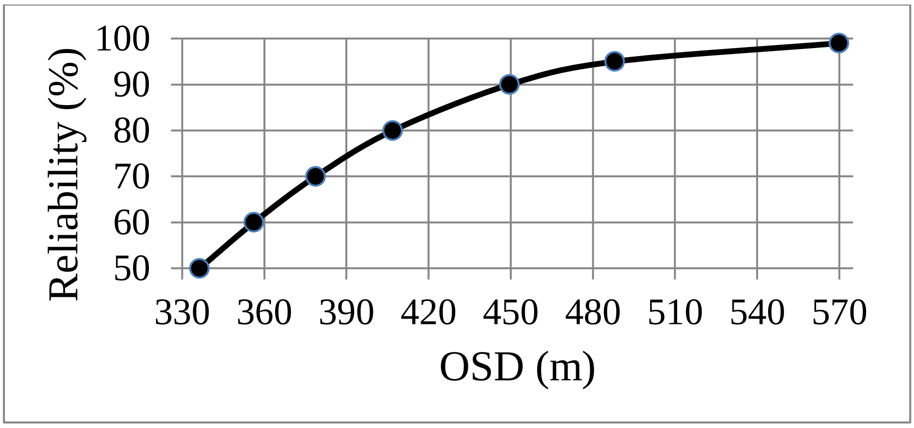

Figure 5: Calibration of OSD against Reliability (Case I) for one-way traffic.

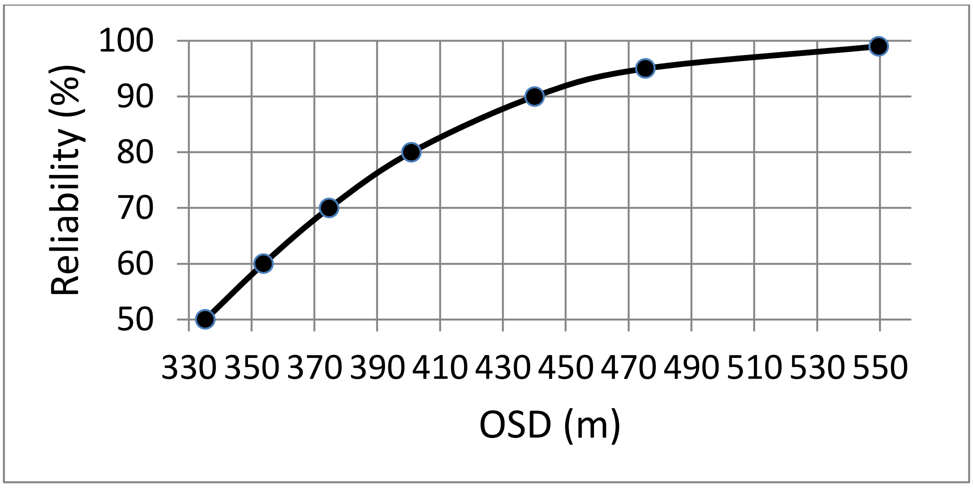

Figure 6: Calibration of OSD against Reliability (Case II) for one-way traffic.

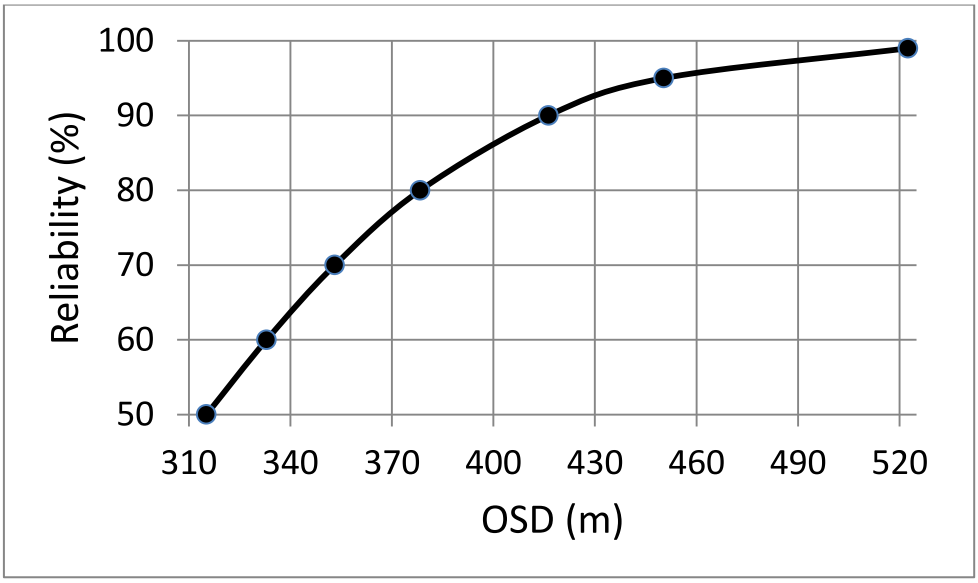

Figure 7: Calibration of OSD against Reliability (Case III) for one-way traffic.

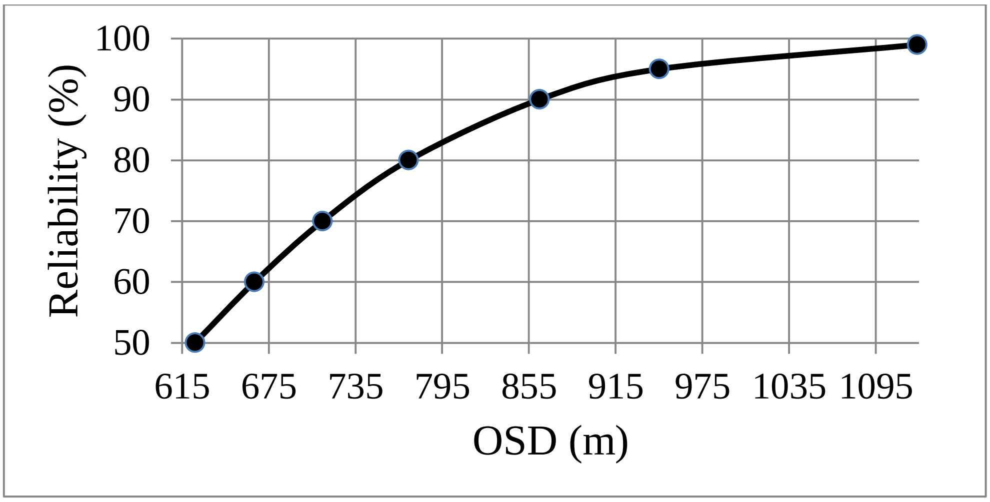

Figure 8: Calibration of OSD against Reliability (Case I) for two-way traffic.

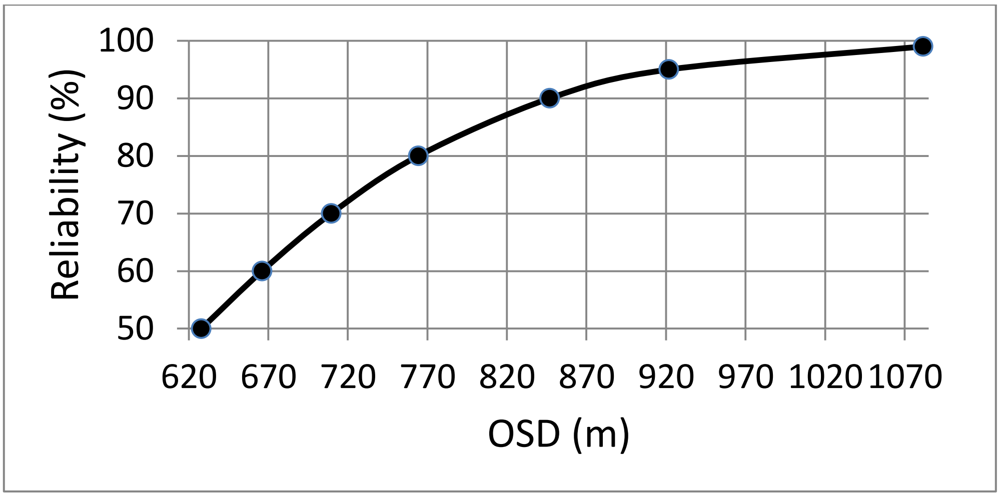

Figure 9: Calibration of OSD against Reliability (Case II) for two-way traffic.

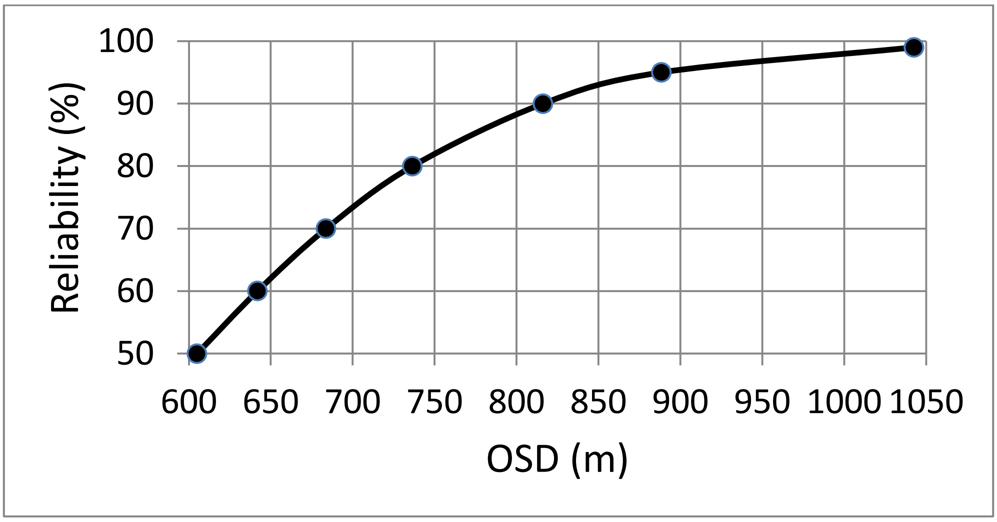

Figure 10: Calibration of OSD against Reliability (Case III) for two-way traffic.

4. Conclusion:

The findings from the present study can be summarized as follows:

1. The distributions of OSD have been derived by Monte Carlo Simulation considering three possible cases of input parameter distribution each for both one-way and two-way traffic conditions. In all the cases, OSD is found to be best represented by lognormal distribution.
2. The derived distributions of OSD are also statistically established by performing Goodness of Fit tests. In all the Cases I, II and III for both one-way and two-way traffic, the lognormal distribution for OSD passes Chi-square Goodness of Fit test at 95% confidence level.
3. The COV of OSD is found to vary from 21.45% to 22.91% for one-way traffic condition,. On the other hand, the COV of OSD varies from 23.66% to 25.66% for two-way traffic. Thus, the variability associated with OSD appears to be significant considering all the cases. Also, the uncertainty of OSD is found to be more in two-way traffic compared to one-way traffic condition. This necessitates the incorporation of probabilistic approach in OSD design which is so far deterministic in nature.
4. With the established distributions and COVs of OSD, the requirement of OSD has been calibrated to achieve various reliability levels and design charts have been prepared considering all the cases of one-way and two-way traffic conditions. A simple design methodology has been suggested whereby a highway can be designed for OSD to achieve particular level of reliability using these charts. Thus, the design of OSD can be accomplished by probabilistic approach. In fact, the charts developed can also serve as useful tools for designers to understand the risk level associated with their design decisions.

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