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Investigating the Effect of Highway Geometric Design on Safety, Using a Safety Indicator within the Design Manual.

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Abstract : *This paper investigates the effect of highway horizontal and vertical alignments design on safety within the context of design provisions in the Design Manual for Roads and Bridges (DMRB) using the Stopping Sight Distance (SSD) and Braking Distance (BD) as safety indicators. The curve radius/superelevations and gradient were investigated. The losses in SSDs and BDs were evaluated as provisions for curve radius/superelevations and gradients beyond the minimum desired values in the manual are adopted in a design. These losses were evaluated for several design speed bands using available geometric design formula and Microsoft Excel Software. At one step and two design speed steps below minimum desired radius, the SSDs lost on average across various design speed band was 25% and 44% respectively while the BDs lost was 35.8% and 63.6% respectively. The loss in SSDs and BDs across design speed bands increased at an average rate of 2.2% and 2.9% as the gradient increases by one percent. The BD which is a component of the SSD showed higher values meaning they are very sensitive. The relationship between the design of the considered parameters and the losses in SSDs and BDs may help give the highway design engineer a measure of how a design parameter that must exceed the minimum desired limit within a section of the entire design is impacting on the safety of the design.*

Keywords: *Design Manual for Roads and Bridges, Geometric design, Highway, Horizontal alignment, Safety.*

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I. .INTRODUCTION

Transportation over the years has become a key aspect of the socio-economic development of any nation. This is evident in the rapid increase in transport infrastructure and improvements in the quality of services that those infrastructures deliver. Road transportation has been a key component in driving growth within the sector. For instance, in the UK, 317 billion vehicle miles was covered, accounting for about 25% of the total passenger kilometres travelled in year 2015 [1]. Sadly, road transportation is the most dangerous of all the means, as evidenced in casualties recorded yearly on roads. There were 1.25 million deaths on roads globally in 2015 alone [2]. This staggering figure underscores the challenge facing road transport globally. This obvious challenge over time have prompted loads of research in accident prevention globally. Road safety and indeed smooth operations hinges on the interaction of the road component, the vehicle component and the road user component. Research have therefore focused on these broad components. Those focused on the road design component over the years have led to the development and subsequent updates in various design manual or guides in different countries leading to improvements in the design of roads that offer a satisfactory level of safety and ease in operations. Most of the research involving the road design component of safety have focused on understanding the relationships between geometric, other design components and safety, using accident records as indices and driver’ s perception under varying geometric and environmental conditions using simulations.

Calvi [3], and Hasan et al [4] carried out driver simulation studies along horizontal curves. Their motivation for isolating horizontal curve for studies stems from statistics indicating that crash rates on curves varies from about 1.5 to four times more on curves than on other road segment [3]. Driver perception and behaviour on curves in the presence of varying horizontal curve elements indicated that curve radius, cross section, visibility and presence of transition curves significantly influenced driving speeds and how a driver negotiates a curve. The findings are consistent with those of Hassan and Sarhan [5] in which speed begins to reduce from the point where the curve becomes visible and on a sizable portion of the curve. From a driver perception and behaviour perspective, on a horizontal curve, several elements, chiefly curve radius is a significant safety factor as the perception of danger will naturally result in a speed reduction.

Sameen and Pradhan [6], used accident data from a police department for a six-year period for a road stretching 44km in other to study the relationship between geometric design variables and the collision rates. The number of vertical curves, the presence of horizontal curves impacted on collision rates significantly. Several studies on the effect of geometric design factors on safety using crash data using various approaches abound in literature [7], [8], [9]. Irrespective of the approach, these studies highlighted highway geometric design parameters that significantly contributed to the recorded crash data. These types of studies and several others have contributed in developing and updating highway design manuals for safety. These notwithstanding, the design Engineers is totally oblivious to the impact on collision rates his design will have using the provisions available within the design manuals. There is therefore the need to quantify, using a suitable parameter of safety in the road design element, the effect of the design on safety of the road users.

This paper is therefore geared toward investigating within the design manuals the relationship between the provisions for geometric design parameters and the effects on safety using a safety indicator provided in the design manuals. Such an investigation will help designers appreciate how adjustments in a geometric design element is impacting on safety as indicated by changes to a safety parameter within the design manual. Design of roads in every country must conform to standards set by appropriate agencies. These manuals are usually the product of research works using field data, practical experiences of professionals within the field overtime etc. As these research works are carried out at separate times, by different authors and updated within the manuals, it is thus useful to understand how various road design elements within the manuals relate with each other and impact on the safety of the proposed design. This work investigates how safety, as indicated by a suitable design element captured in a design manual is changing as the design provisions for horizontal and vertical alignment changes in line with the provisions of the design manual.

II. Methodology

The Design Manual for Roads and Bridges (DMRB) was used in this investigation. The DMRB contains requirements, advice and other published documents relating to works on motorways and all-purpose trunk roads in the UK [10]. The manual makes provisions for several geometric design elements for a range of design speed bands. Within each design speed, the manual provides some desired minimum value or absolute maximum values for several geometric elements. It also allows for providing within a given design speed, values of some geometric elements corresponding to one step and two design speed steps below the speed under consideration. The effect of using design values of one step and two steps below the desired minimum for specific design speed on safety was investigated for horizontal and vertical alignments.

The sight distance feature deals with the carriageway length visible to the driver in both the horizontal and vertical plane and considered the most important feature in the safe and efficient operation of highways [11]. The Stopping Sight Distance (SSD) was used as a safety indicator within the design manual in this investigation. The Braking Distance (BD) component of the SSD was also considered. The Breaking Distance component is significant because it is that distance available to a driver after brakes have been applied to manoeuvre the car away from perceived danger and to a halt.

2.1 Effect of Horizontal Alignment on Safety

The curve radius and superelevation were the key elements used in investigating impact of horizontal alignment on safety. The DMRB provides values of desired minimum curve radius and superelevation for each design speed band as well as for one step and two design speed steps below the desired minimum. The corresponding SSDs for the minimum desired and those of the design speed steps were matched. Excel software was used in evaluating the percentage loss in SSDs as lesser Radius (Radius of one and two design speed steps below minimum desired) are used within a given design speed. Also, the BD was calculated using the formula:

$BD = v^2/2w$ ……………………………………………………………………(1)

where v is the design speed and w the deceleration rate, w is usually taken as 0.25g in the UK [11] and g is the acceleration due to gravity.

The loss in BD for one step and two steps below desired minimum radius/superelevation was also evaluated. These was done for design speed bands of 120km/h, 100km/h, 85km/h, 70km/h and 60km/h. In each case the loss in SSD and BD was calculated as Radius lower than minimum required was used.

2.2 Effect of Vertical Alignment on Safety

On a descending gradient, the driver will have a substantial sight distance that can only be limited by obstructions on the road environment. Thus, the ascending gradient only was investigated to see the losses in sight distances as the gradient increases. The following relationship by Mathew and Rao [12] incorporates the effect of gradient on SSD calculations and was used to calculate the SSDs:

$SSD = vt + [v^2/(2g(f \pm 0.01n))]$ ……………………………………………………….. (2)

Where v is the design speed in m/s, g is acceleration due to gravity, f is the friction factor usually 0.25 for the UK [13] and n is the percentage gradient.

The SSDs and BD was evaluated for each design speed band and corresponding to gradients 0,1,2,3,4,5,6,7,8,9,10 percent. The DMRB allows a desirable maximum gradient of 3% and 6% for motorways and all-purpose single carriageways respectively. For ease of operations, it sets 4% as the absolute maximum for motorways and 8% as absolute maximum beyond which safety is critically affected. The losses in SSDs and BDs as design gradient shifts at critical points set out in the design manual are calculated and the results presented and discussed in the following section.

III. Results and Discussion

TABLE 1 below shows the design provision in the DMRB for the parameters involved in the investigation.

Table 1: Design provisions for geometric design elements as contained in the DMRB. [14]

DESIGN SPEED kph	120	100	85	70	60	50	V^2/R
STOPPING SIGHT DISTANCE m							
Desirable Minimum	295	215	160	120	90	70	
One Step below Desirable Minimum	215	160	120	90	70	50	
HORIZONTAL CURVATURE m.							
Minimum R* without elimination of Adverse Camber and Transitions	2880	2040	1440	1020	720	520	5
Minimum R* with Superelevation of 2.5%	2040	1440	1020	720	510	360	7.07
Minimum R* with Superelevation of 3.5%	1440	1020	720	510	360	255	10
Desirable Minimum R with Superelevation of 5%	1020	720	510	360	255	180	14.14
One Step below Desirable Minimum R with Superelevation of 7%	720	510	360	255	180	127	20
Two Steps below Desirable Minimum Radius with Superelevation of 7%	510	360	255	180	127	90	28.28
VERTICAL CURVATURE							
Desirable Minimum* Crest K Value	182	100	55	30	17	10	
One Step below Desirable Min Crest K Value	100	55	30	17	10	6.5	
Absolute Minimum Sag K Value	37	26	20	20	13	9	
OVERTAKING SIGHT DISTANCES							
Full Overtaking Sight Distance FOSD m.	*	580	490	410	345	290	
FOSD Overtaking Crest K Value	*	400	285	200	142	100	

3.1 Effect of horizontal alignment design on Stopping sight and braking distances

The losses in SSDs and BDs as one adopts design radii less than the minimum desired radius within a specific design speed was calculated for each design speed band except 50km/h and is presented as follows. The TABLE 2 below shows typical results of analysis carried out for each considered speed band.

T**able 2**: Typical results of investigation of effect of design radius on losses in SSD and BD

Design Speed of 120km/h			
	Minimum Desired	**One Step below Minimum.**	**Two Steps below Minimum**
Radius (m)	1020	720	510
SSD (m)	295	215	160
SSD Lost (m)	0	80	135
% SSD Lost	0%	27%	46%
Braking Distance (m)	227	147	92
% BD lost	0%	35%	60%

The result in TABLE 2 above is typical of those of other design speeds considered. It indicates that losses in SSD and BD occur as a design adopts the one step and two steps below minimum radius in the design guide. The Figs below summarizes the results for all the design speeds investigated.

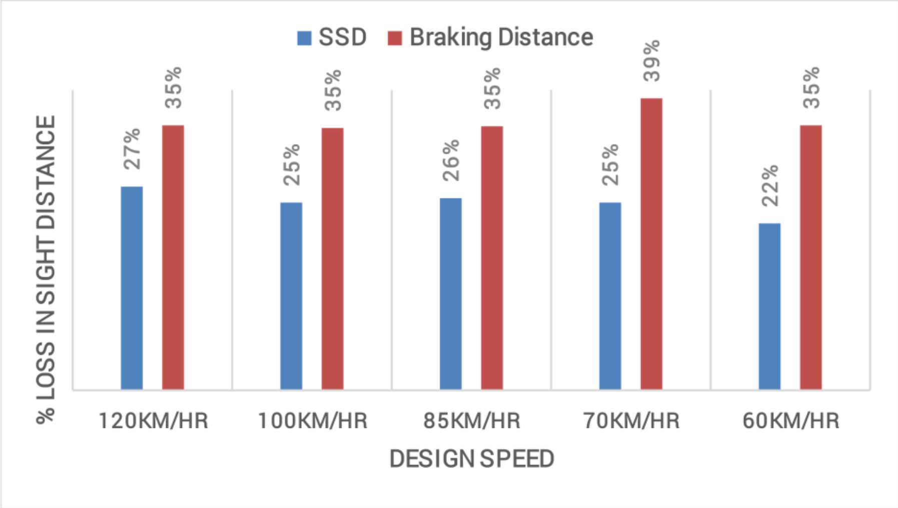


Figure 1: Comparing losses in sight distances for various design speeds at one step below minimum desired design radius

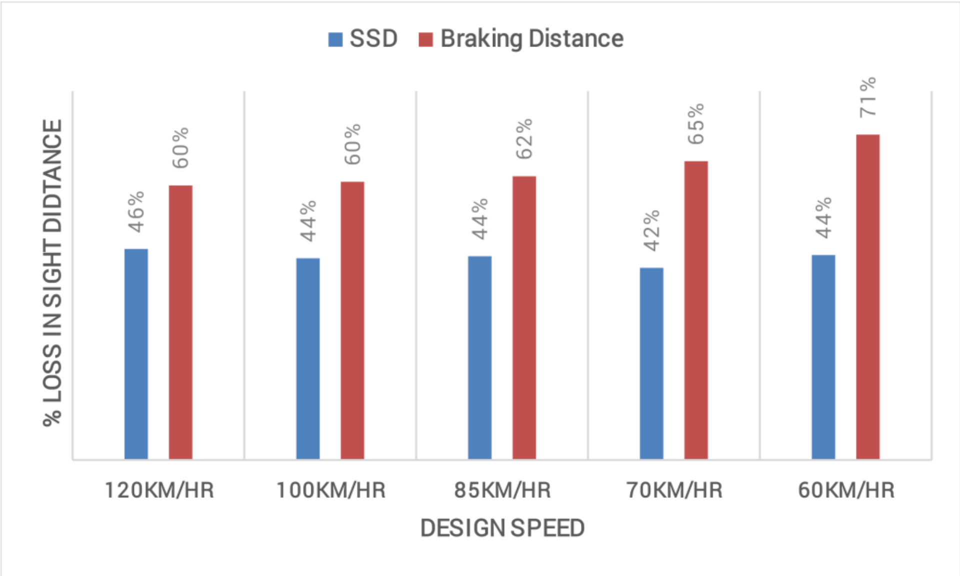


Figure 1: Comparing losses in sight distances for various design speeds at two steps below minimum desired design radius

At one design speed step below minimum desired, there is no marked variation in sight distance lost as we go from higher design speed band to a lower one. On average, there is a loss in SSD of about 25% across design speed bands as one step below minimum design radius are employed. Comparatively, a significant difference is observed in the losses in each design speed between the SSD and BD. The loss on average for the BD across design speed band is 35.8%, a difference of 10% more than those of the SSD. At two design speed steps below (even lesser radius within a specified design speed), fig 2 above shows the variation in losses in SSDs across design speed bands are not much. The loss in SSD from the desired minimum design radius across design speeds is about 44% on average. The BD on the other hand shows a steady increase in losses as the design speed reduces beginning from design speed of 100km/h, overall an average loss of 63.6% across design speed bands, a difference of about 20% more than the SSD.

Across design speeds, at minimum desired design radius, sufficient SSDs and BDs are available. As lower radii are employed within the same speeds, it is expected that the available sight distances will be lesser giving rise to losses in SSDs and BDs. The lower the curve radius, the more losses are expected. This is reflected in the results of both SSDs and BDs above. The SSD which includes the BD are safety elements build into the road design. Losses in these elements due to design is indicative of how less safe the design is becoming.

3.2 Effect of vertical gradient on stopping sight and braking distance
The charts below show the losses in SSDs and BDs for the various design speed bands as design gradients increases vertically upwards from a beginning gradient of 0%.

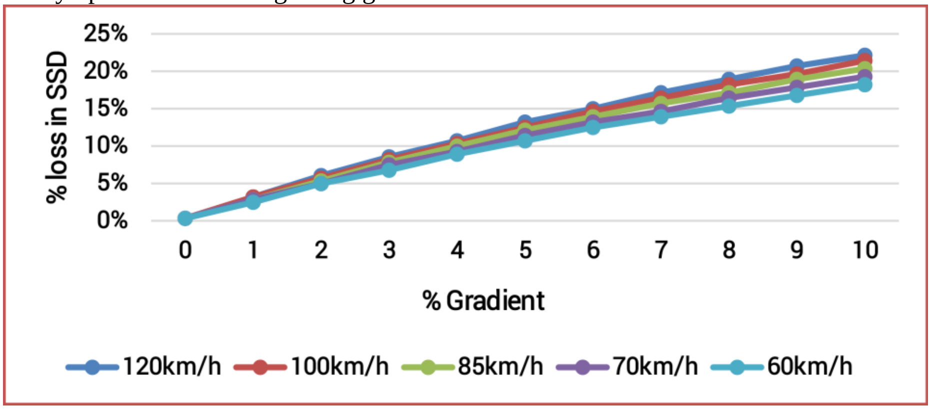
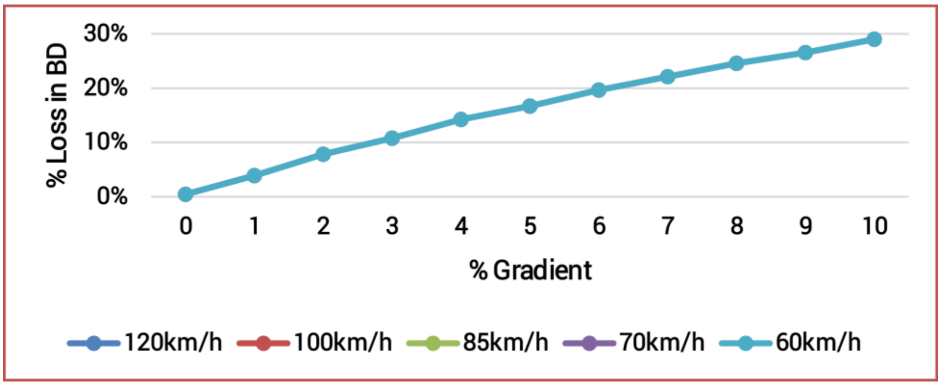


Figure 2: Effect of increasing positive gradient on SSDs for various design speeds bands



Figu**re 3**: Effect of increasing positive gradient on BDs for various design speeds bands

Fig 3. above shows that for each design speed, the losses in SSDs increases gradually for every percent rise in gradient. The losses for each gradient is seen to also be increasing as the design speed band increases. For every 1% change in gradient, the loss in SSD is on average 2.2%. The loss in BD across gradient is gradual, rising at an average of 2.9% for every percentage rise in gradient. The results show that unlike in the case of SSDs, the losses in BD corresponding to each gradient is constant across all design speed band. In other to analyse the impact of this rising gradient on safety as indicated by losses in SSDs and BDs, the summary of the losses in these distances at critical gradients in the DMRB is presented in TABLE 3. The losses shown below takes it reference from a flat terrain having a 0% gradient.

Table 3: Summary table comparing losses in SSD and BD at critical gradients

Design Speed (km/h)	% loss in SSD @ 4% grade	% loss in SSD @ 8% grade	% loss in SSD @ 9% grade	% loss in BD @ 4% grade	% loss in BD @ 8% grade	% loss in BD @ 9% grade
120	11	19	20	14	24	26
100	10	18	20	14	24	26
85	10	17	19	14	24	26
70	9	16	18	14	24	26
60	9	15	17	14	24	26

At 4% gradient (the absolute maximum for motorways), the loss in SSD from a flat terrain with 0% grade is at least 10% considering motorways have design speeds upwards of 100km/h while the loss is 14% for BD. Beyond this limit, the losses in SSD and BD for every percent rise in grade remains 2.2% and 2.9% respectively and is indicative of how less safe the road gets. At the other extreme for single lane all-purpose roads where the absolute maximum grade is 8%, the table shows losses in SSD and BD of 15% and 24%

respectively for the design speed of 60km/h and increases with design speed increases for the SSDs while the losses in BD remains the same with increases in design speeds.

IV. Conclusion

This work has been focused on investigating within the context of the provisions in the DMRB, the effect of designing horizontal and vertical alignment of a road on the safety of the road using the SSD and BD as safety indicators. As the radius/superelevations, lower than the minimum desired are employed as directed in the DMRB within each design speed band, losses in SSDs and BDs for each of these design speed band were found. The findings are not applicable to a section having combined vertical and horizontal elements. These percentage losses in SSDs and BDs are indicative of how less safe the alignment is getting as lower radius, below the desired minimum is employed for a specific design speed. In the vertical alignment, the loss in SSD and BD on a rising gradient were found for every one percent rise in gradient and for the various design speed bands. Losses in SSDs and BDs were increasing at 2.2% and 2.9% respectively on average across all design speed band. By understanding the relationship and quantifying losses in SSD and BD as various design provisions for vertical and horizontal alignment are employed, the highway engineer now has a measure of how safety of the design is deteriorating. In selecting horizontal and vertical alignment elements that must be lower than minimum desired or other benchmarks in the design manual, the losses in either of the SSD and BD can be fixed, and working by a reverse process, determine the corresponding radius and gradients.

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