THE RELATIONSHIP BETWEEN GEOMETRIC DESIGN STANDARDS AND SAFETY

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ABSTRACT

Geometric design standards are mainly based on logically derived relationships and engineering judgements which are seldom validated by accident studies. Consequently, it is difficult to assess the likely safety consequences of departures from standards. This paper compares the results of studies in different countries and summarizes current international knowledge of the relationships between safety and the principal non-intersection geometric design parameters. In general, there is broad international agreement on these relationships.

Many studies have attempted to relate geometric elements and accident rates but only a limited amount of reliable information is available and quantifying the safety impact of marginal changes in the values of geometric design parameters is difficult. It appears that significant changes in the value of many geometric design standard elements are unlikely to result in large increases in accident rates and it is concluded that the available international information provides a good indication of the differences in accidents which would result from departures from design standards or from alternative route alignments.

INTRODUCTION

The road environment has been identified as a prime cause of accidents, contributing to about 17 to 34 percent of accidents and as the sole contributing factor for 2 to 3 percent of accidents. Geometric design standards or guidelines specify appropriate minimum, maximum and desirable values of the visible road elements; these values are usually specified separately although many are interrelated. Although based on similar design approaches, there are substantial differences between the standards specified by different countries (1). Since these standards are mainly based on logically derived relationships rather than on safety studies, it is difficult to quantify the safety implications of departures from standards due to environmental or terrain restrictions. This paper draws general conclusions on the available international knowledge on the relationships between design parameters and safety. It is based on an investigation (2) carried out as part of a study into the potential use of Advanced Transport Telematics for the modification of geometric design standards under the European Union DRIVE (Dedicated Road Infrastructure for Vehicle safety in Europe) Research Programme.

THE RELATIONSHIP BETWEEN SPEED AND SAFETY

Speed is one of the major parameters in geometric design and safety is synonymous with accident studies. For example, Finch et al. (3) recently concluded that a reduction of 1.6 km/h (1 mph) in the average speed reduces the incidence of injuries by about 5%. Also it is generally accepted that there are substantial safety benefits from lower speed limits. For example, reducing rural speed limits from 100 km/h to 90 km/h has been predicted to reduce casualties by about 11% (4). It is interesting to note that the relationship between the design speed and the speed limit is not referred to in the geometric design standards of many countries (1).

ROAD TYPE AND SAFETY

Few studies have related detailed geometric standards to accident rates over entire road networks and it has been difficult to draw reliable conclusions except in broad terms. For example, Hearne (5) related traffic flow and road inventory information to accident occurrence on rural sections of the National Road Network in Ireland using multiple regression analysis. The only variables which affected accident rates significantly, besides traffic volume which was the dominant variable, were the number of roadside developments and the absence of hard shoulders.

Only a limited number of studies of the accident rates associated with each road type have been published (although such rates are commonly used in the benefit-cost analysis of new road schemes). In 1993 Brannolte et al. (6) reported the results of a comprehensive study of non-intersection accident rates for 12 different road types in Germany. The casualty plus severe damage accident rates for the various types of four- and six-lane roads did not vary substantially, but there were large differences in the total accident rates; undivided four-lane roads were considerably more dangerous than divided ones which is generally accepted. It is interesting to note that three-lane roads (two lanes in one direction for about 1 km, followed by two lanes of similar length in the opposite direction) had the lowest accident rates of any undivided road type (the reported rates were even lower than for motorways). The relative safety of three-lane roads was also reported by Grime (7) while an investigation of the effectiveness and safety of auxiliary passing lanes on two-lane roads in the United States (8) concluded that accident rates did not increase and that the number of accidents were probably reduced.

As regards to the number of lanes, NCHRP Report 197 (9) stated that "as the number of lanes increases, the accident rate decreases" which is supported by Brannolte et al. (6).

CROSS SECTION ELEMENTS

The widths of the various cross section elements affect the driver's capability to perform evasive maneuvers and determine the lateral clearances both between vehicles and between vehicles and other road users.

(a) Lane Width

Most studies were limited to two-lane rural roads and showed that accident rates decreased with increased width (30). However, Hearne's results (5) suggested that there was a marginal increase in accident occurrence with an increase in carriageway width. Hedman (10) noted that some results indicated a rather steep decrease in accidents with increased width of carriageway from 4m to 7m, but that little additional benefit is gained by widening the carriageway beyond 7m. This is supported by the NCHRP Report 197 (9) conclusion that there is little difference between the accident rate for a 3.35m and a 3.65m lane width. However, studies on low-volume rural roads indicate that accidents continue to reduce for widths greater than 3.65m, although at a lower rate (30).

Yagar and Van Aerde (11) found that the passage of a vehicle requires a minimum lane width and that any additional width beyond this minimum allows one to drive faster and / or with a greater measure and perception of safety. For lane widths from 3.3m to 3.8m, they reported that the operating speed is decreased by approximately 5.7 km/h for each 1m reduction in width of the road.

In Denmark (12), as the lane width increases the relative accident frequency decreases: for road widths of under 6m, there was an increase in the risk of both injury accidents and severe injury accidents. This is supported by Srinivasan (13) who reported that "the accident rate of a 5m road was about 1.7 times that of a 7.5m road". NCHRP Report 197 (9) suggested that widening lanes from 2.7m to 3.7m would reduce accidents by 32 percent. A comprehensive Swedish study reported that, for roads with 90 km/h speed limits and similar alignments, increases in roadway width (carriageway plus shoulders) up to 13m give significant reductions in accident rates (16). However, more recent Swedish work concluded that it was not possible to detect any statistically significant differences in accident rates between wide and narrow roads (14): of the three road-width classes used (6-8.5m, 9m and 10-13m), the 9m roads had a higher accident rate irrespective of the decade of construction.

A small number of predictive models have been developed: TRB Special Report 214 (15) includes a prediction model for non-intersection accidents on two-lane rural roads with varying lane and shoulder widths. The Swedish Road and Traffic Research Institute developed an accident prediction model (16) for different paved widths, classes of alignment and vehicle mileage.

(b) Shoulder Width

There have been a number of studies of the relationship between the shoulder width and the accident rate. As noted by Hedman (10), more recent studies show a decrease in accidents with increases in width from 0m to 2m, and little additional benefit is obtained above 2.5m. However, NCHRP Report 197 (9) concluded that, on multi-lane undivided and divided highways, shoulders that will not accommodate a parked vehicle off the traveled way increase the accident rate. Also, on tangents, as the shoulder width increases beyond the minimum, the safety benefit becomes insignificant; on curves, as the shoulder width increases, the accident rate decreases; on multi-lane divided highways, as the median shoulder width increases, accidents increase. For this reason median shoulders are not included in the design standards of some European countries (1).

As TRB Special Report 214 (15) noted, the literature does not provide an entirely consistent model of the simultaneous effects of lane width and shoulder type on accidents. It also noted that accident rates decrease with increases in lane and shoulder width and that widening lanes has a greater safety benefit than widening shoulders.

(c) Median Width

A median separates the traffic lanes in opposite directions. Srinivasan (13) found that on high-speed roads with two or more lanes in each direction, medians improve safety in a number of ways, for example by reducing the number of head-on collisions. The Danish design standards (12) include a table showing the relationship between the median width, the accident frequency of the through section and a severity index for medians with and without a crash barrier; medians, particularly with barriers, reduce the severity of accidents, but medians wider than 3.0m show little additional benefit. In contrast, United States studies show continuing reductions in the number of injury crashes for widths up to 12m and over (30).

(d) Climbing Lanes

A climbing lane is an extra traffic lane provided on uphill gradients for slow-moving vehicles. Hedman (10) quotes a Swedish study which concluded that climbing lanes on rural two-lane roads reduced the total accident rate by an average of 25%; 10% to 20% on moderate upgradients (3% to 4%) and 20% to 40% on steeper gradients. It was also observed that additional accident reduction can be obtained within a distance of about 1km beyond the climbing lane. In earlier studies, Jorgensen (17) found no change in accident experience in the United States due to the provision of climbing lanes while Martin and Voorhees (18) found a 13% reduction in accidents in the UK.

General conclusions on the relationship between cross section elements and safety.

- As the lane width increases above the minimum, the accident rate decreases. However, the marginal rate diminishes with increased lane width.
- On multi-lane roads, the more lanes that are provided in the traveled way, the lower the accident rate.
- Shoulders wider than 2.5m give little additional safety benefit. As the median shoulder width increases, accidents increase.
- The presence of a median has the effect of reducing specific types of accidents, such as head-on collisions. Medians, particularly with barriers, reduce the severity of accidents.
- From the limited information available, it appears that climbing lanes can significantly reduce accident rates.

ALIGNMENT

The horizontal and vertical alignments can restrict the driver's speed, sight distance and overtaking opportunities. It is difficult to separate the safety effects of the different alignment elements.

(a) Stopping Sight Distance

Stopping sight distance is the distance required by a driver to stop safely in order to avoid striking an object on the road. This is the minimum sight distance provided and is one of the major factors controlling the cost and the environmental impact of road design since its provision affects the size of many other design elements. Although minimum stopping sight distances are specified on safety grounds, little information is available on the relationship between stopping sight distance and safety. However, it is generally accepted that short sight distances are dangerous.

- Yagar and Van Aerde (11) found, contrary to their prediction, that sight distance was not a contributory factor in controlling vehicle speeds.
- A UK study (19) reported that there is little erosion of safety resulting from sight distances below absolute minimum design standards on "clean" sites (no accesses, intersections, etc.); it was also noted that accident rates rise steeply at sight distances below 100m; fitted graphs of sight distance versus accident rate show that sight distances greater than about 500m have little effect on accidents.
- TRB Special Report 214 (15) stated that a study carried out in the United States under carefully controlled conditions found that accident frequencies were 52 percent higher at sites with sight reduction than at the control sites.
- Hall and Turner (20) found that inadequate stopping sight distance does not guarantee that accidents will occur.
- A Swedish study has shown that accident rates decrease with increasing average sight distance, especially for single-vehicle accidents in darkness (21); also that accidents decrease with "decreased density of minima" for the sight distance.

(b) Overtaking Sight Distance

The overtaking sight distance is the distance ahead which must be visible to the driver of an overtaking vehicle in order to allow completion of the overtaking maneuver safely. Certain sight distances are considered undesirable in some countries since they may appear adequate for overtaking (1). However, no relationship between the length or proportion of overtaking sight distance and accidents could be located.

(c) Horizontal curvature

Numerous studies have investigated the relationship between horizontal curvature and accidents. As Srinivasan (13) noted, an isolated narrow curve in an otherwise straight alignment is more dangerous than a succession of curves of the same radius, and horizontal curves are more dangerous when combined with gradients and surfaces of low coefficients of friction. Similarly Brenac (22) reported that studies based on detailed accident data show that short radius curves are only dangerous if there is a road alignment anomaly such as a difficult isolated bend in an otherwise easy section or if the bend has an internal defect. Brenec also quoted (27) a recent French study which showed that accidents at bends depend on two significant variables: the radius and the straight lengths on both approaches. Glennon et al (23) reported that the average accident rate for highway sections which include horizontal curves is about three times that for horizontal tangents. A number of studies have indicated that horizontal realignment of rural highways is the most efficient way of increasing safety; reductions in the number of accidents of the order of 80 percent have been reported (13, 24). Table 1 shows the prediction model developed from a Swedish study on roads with a 90 km/h speed limit (16).

The UK Department of Transport (25) include graphs which compared accident rates for horizontal curvature to a base accident rate by means of a multiplier which agree closely with the Swedish values shown in Table 1. The difference between straight sections and bends becomes significant at a radius of about 1000m. The UK data indicate continually increasing accident rate with reducing radius. This increase in accident rate becomes particularly apparent at curve radii below 200m. Simpson and Kerman (26) noted that low radius curves result in much shorter curve lengths and that the overall implications for accidents may not be as bad as would appear.

A comprehensive French study quoted by Brenac (22) found that curve radii below 200m limited the mean speed on bends to less than 90 km/h. This finding is consistent with work carried out by the University of Southampton quoted by Simpson and Kerman (26), which found that there is only a minor decrease in the speed adopted by drivers approaching bends of radii which are two UK design-speed steps below that for which the road is designed.

TABLE 1 Accident Reduction Factors for Various Increases in Horizontal Radii (proportion of original accident rate) *(16)*

	To (m)		
From (m)*	500	700	1 500
300	0.25	0.35	0.45
500	-	0.10	0.30
700	-	-	0.20

*1m = 3.28ft

(d) Transition Curves

Some studies have concluded that transition curves are dangerous because of driver underestimation of the severity of the horizontal curvature (24, 27). Stewart (28) quotes a California Department of Transportation study involving a rigorous comparison of over 200 bends, both with and without transitions curves; those with transitions had, on average, 73% more injury accidents (probability < 0.01). Also the Department's report "Accidents on Spiral Transition Curves in California" recommends against any use of these curves. However, it is understood that recent studies in Germany and the UK (to be published) have concluded that the impact of transitions on safety is neutral.

(e) Gradients

Steep gradients are generally associated with higher accident rates. Hedman (10), quoting Swedish research, stated that grades of 2.5 and 4.0 percent increase accidents by 10 and 20 percent, respectively, compared with near-horizontal roads.

- Glennon et al. (23), after examining the results of a number of studies in the United States, concluded that grade sections have higher accident rates than level sections, steep gradients have higher accident rates than mild gradients and downgradients have higher accident rates than upgradients. UK design standards (29) included a graph relating the base accident rate to that on gradients which concurs with Glennon's conclusions. Simpson and Kerman (26) noted that the overall accident implications of steep gradients are not as severe as would first appear since steeper gradients have shorter lengths.
- NCHRP Report 197 (9) concluded that the accident rate increases with gradient on curves.

(f) Convex (Crest) Curves

Minimum vertical convex curves are generally based on the provision of stopping sight distance at all points along the curve. TRB Special Report 214 (15) includes an equation from which the accident frequency on a segment of roadway containing a single crest vertical curve and its tangent approaches can be estimated; it concludes that the geometry of vertical curves is not known to have a significant effect on accident severity. However, Srinivasan (13) stated that "frequent changes in vertical alignment also result in a reduction in sight distance at the crest of vertical curves and these have been shown to be related to accidents, both in respect of frequency of occurrence and degree of sight obstructions"; the combination of gradient and superelevation on curves is important.

(g) Concave (Sag) Curves

The length of a concave curve is related to the stopping sight distance, the algebraic difference in gradients, the upward spread of the headlamps, etc. There is a lack of information on the safety impacts of concave curves. It has been stated that 'relaxations' in stopping sight distance on concave curves in relatively flat terrain have no significant effect (29).

General conclusions on the relationship between alignment and safety

- In most studies it has not been possible to fully eliminate the effects of non-alignment variables, such as road widths, presence of intersections, etc. Also it is difficult to distinguish the separate impacts of the various alignment elements.
- There appears to be little erosion of safety resulting from the use of sight distances below the minimum values specified in geometric design standards, although there is a significant increase in the accident rate for sight distances below 100m.
- A road alignment anomaly such as an isolated narrow curve in an otherwise straight alignment is more dangerous than a succession of curves of the same radius. Also horizontal curves are more dangerous when combined with gradients and surfaces with low coefficients of friction.
- Horizontal curves have higher accident rates than straight sections of similar length and traffic composition; this difference becomes apparent at radii less than about 1000m. The increase in accident rates becomes particularly significant at radii below 200m. Small radius curves result in much shorter curve lengths and the overall implications for accidents may not be as severe as would first appear.
- There is only a minor decrease in the speed adopted by drivers approaching bends of radii which are significantly less than the minimum radii specified for the design speed. However, curve radii below 200m have been found to limit the mean speed to 90 km/h.
- More recent work suggests that the impact of transition curves is neutral.
- Accidents increase with gradient, and downgradients have considerably higher accident rates than upgradients. However, the overall accident implications of steep gradients may not be very severe since steeper gradients are shorter.
- The geometry of vertical curves is not known to have a significant effect on accident severity.

THE SAFETY IMPLICATIONS OF REDUCING DESIGN STANDARDS

Table 2 indicates the safety consequences of reducing the design speed from 100 km/h to 80 km/h. The design parameter values shown are mean values for European design standards (1) while the predicted increases in accidents are based on a synthesis of the information contained in this paper. Most design parameters show strong relationships to safety except for gradients, vertical curvature and overtaking sight distance. Reducing the horizontal curvature by the specified design step reduction results in the greatest effect on the accident rate. A reduction in design speed from 120 km/h to 100 km/h would show significantly smaller increases in accidents than those shown in Table 2.

DISCUSSION

The relationship between geometric design factors and accident rates is complex and not fully understood. Relatively little information is available on the relationships between many geometric elements and accident rates, although it has been clearly shown that very restrictive geometric elements such as very short sight distances or sharp horizontal curvature result in considerably higher accident rates and that certain combinations of elements cause an unusually severe accident problem. However, it appears that significant reductions in the values of some of the elements specified in geometric design standards (equivalent to one design speed step) do not result in large increases in accident rates.

There are major difficulties in comparing and assessing the reliability of the available studies due to differences in definitions and parameters used, types of accidents included, the omission of traffic volume, speed and composition information, presence of cyclists or roadside development, lack of statistical control, etc. Also comparisons between studies carried out in different countries must be treated with caution because of differences in driver behaviour, enforcement practices and the actual road environment. However, there is broad agreement on the general relationships between geometric design elements and accident rates. Consequently, for the purposes of evaluating the safety impacts of lower physical design standards or for comparing the safety of alternative route alignments, the available information should provide a reasonable indication of the likely differences in expected accidents.

TABLE 2 Safety Consequences of Typical Reductions in Geometric Design Standards Relating to a Drop in Design Speed from 100 km/h to 80 km/h

Geometrical element	Typical reductions (100-80 km/h)[a]		Predicted increase in accidents (%)
	From	To	
Lane Width (m)*	3.7	3.5	10
Shoulder Width (m)	1.5	1.0	15
Min Stopping Sight Distance (m)	170	110	10
Min Passing Sight Distance (m)	590	460	Minimal
Max Gradient: (0.5km)	5%	6%	
Upgradient			-2
Downgradient			3
Overall			1
Min Convex Radius (m)	8700	4500	-2
Min Concave Radius (m)	4000	2500	Minimal
Min Horizontal Curve Radius (m)	460	260	20 - 32

(a) Based on European design standards (1)

*1m = 3.28ft

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